Robotic Servicing of Geosynchronous Satellites (RSGS) Proposers Day

Joseph Parrish, Program Manager
DARPA Tactical Technology Office

Briefing prepared for Robotic Servicing of Geosynchronous Satellites (RSGS) Proposers Day

May 22, 2019

TTO Strategy
Enterprise Disruption

Dr. Tom Beutner, Deputy Director
DARPA Tactical Technology Office

May 22, 2019

Disrupting the Adversaries' Calculus

- The U.S. military industrial base is great at making very capable, complex systems
- Our risk-averse processes incentivize performance over cost and schedule
- The result is orders of battle that are predictable, stove-piped, vulnerable, and non-responsive to emerging threats
- To present our adversaries with scenarios that create dilemmas within or completely disrupt their decision calculus, we must disrupt our own warfighting enterprises

Four Domains, Reimagined

After Uncontested Space

www.darpa.mil

RSGS Program Overview

Joseph Parrish
RSGS Program Manager

May 22, 2019

Why does DARPA think this is important?

Problem: Very high value satellites are isolated and un-serviced

- Anomalies are diagnosed with indirect data and inferences, with great potential for misinterpretation
- There are few opportunities to correct anomalies, even if understood
- End-of-life (EOL) is often dictated by propellant exhaustion, even though other systems are functional

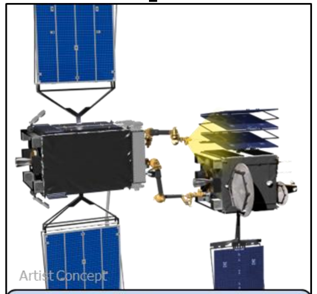




The lack of on-orbit inspection and servicing leads to strategic vulnerability and economic cost

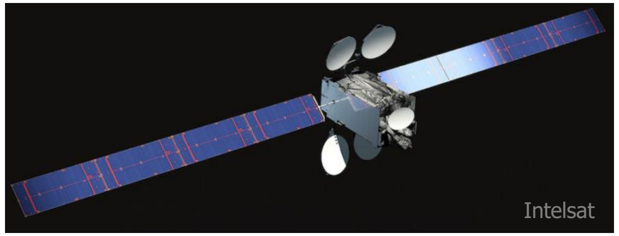
No end in sight for these anomalies and EOL issues

Inspect



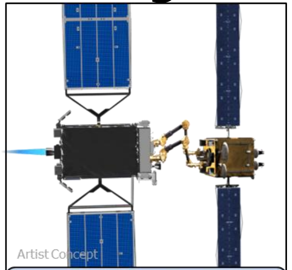
Cooperatively **inspect** spacecraft experiencing anomalies

Intelsat 29e, 2019, fuel leak?



Attribution and diagnostics via survey and ultra-close inspection

Tug

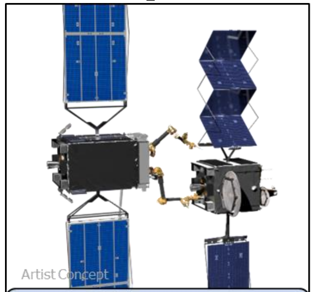


Cooperatively **assist** with orbit adjustments

AEHF 1, 2010, propulsion system anomaly

Rescue, relocation, retirement, fuel-use deferral

Repair

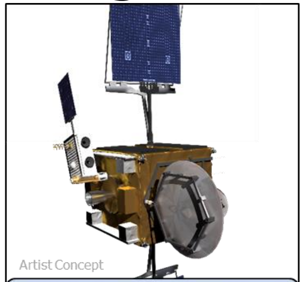


Cooperatively **correct** mechanical problems

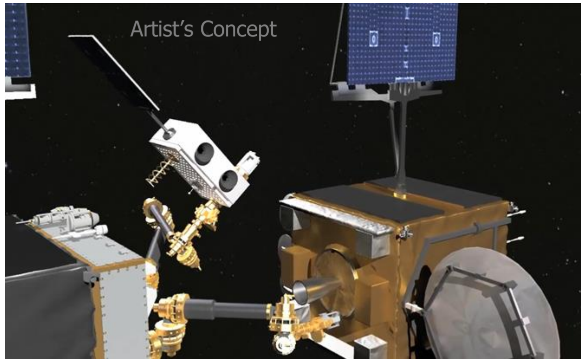
New Dawn, 2011, stuck C-band reflector

Very high payoff; low occurrence rate

Augment



Cooperatively **install** self contained payloads on-orbit



Upgrade, tech refresh, mission adaptation

None of these capabilities exist today in GEO

DARPA's answer: Robotic Servicing of Geosynchronous Satellites (RSGS)

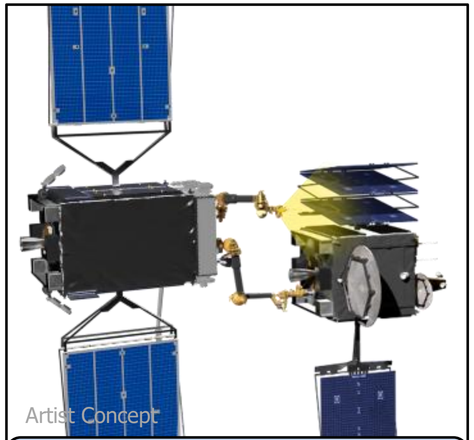
Goal: To create a dexterous robotic operational capability in geosynchronous orbit

Benefits:

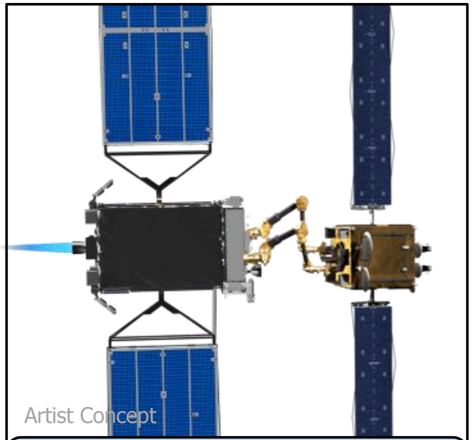
- Increased resilience for the current U.S. space infrastructure
- The first concrete step toward a transformed space architecture with revolutionary capabilities

Launch: Q4FY22 (notional)

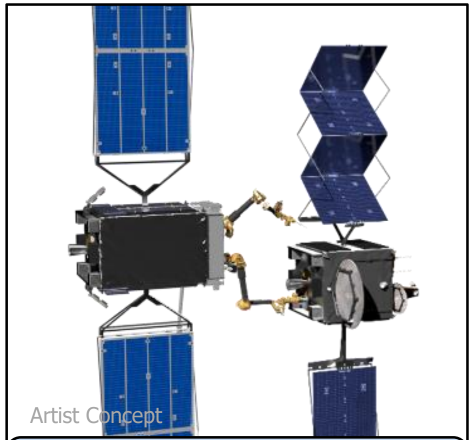
Approach: Public-private partnership



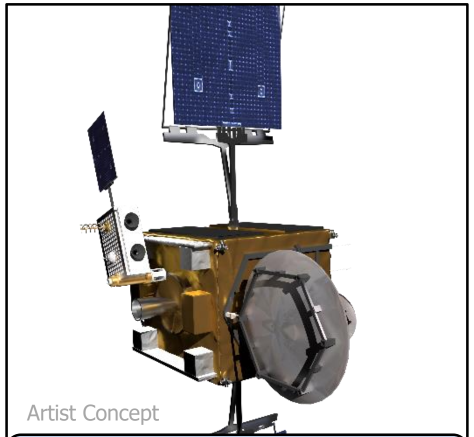
Cooperatively **inspect** spacecraft experiencing anomalies



Cooperatively **assist** with orbit adjustments

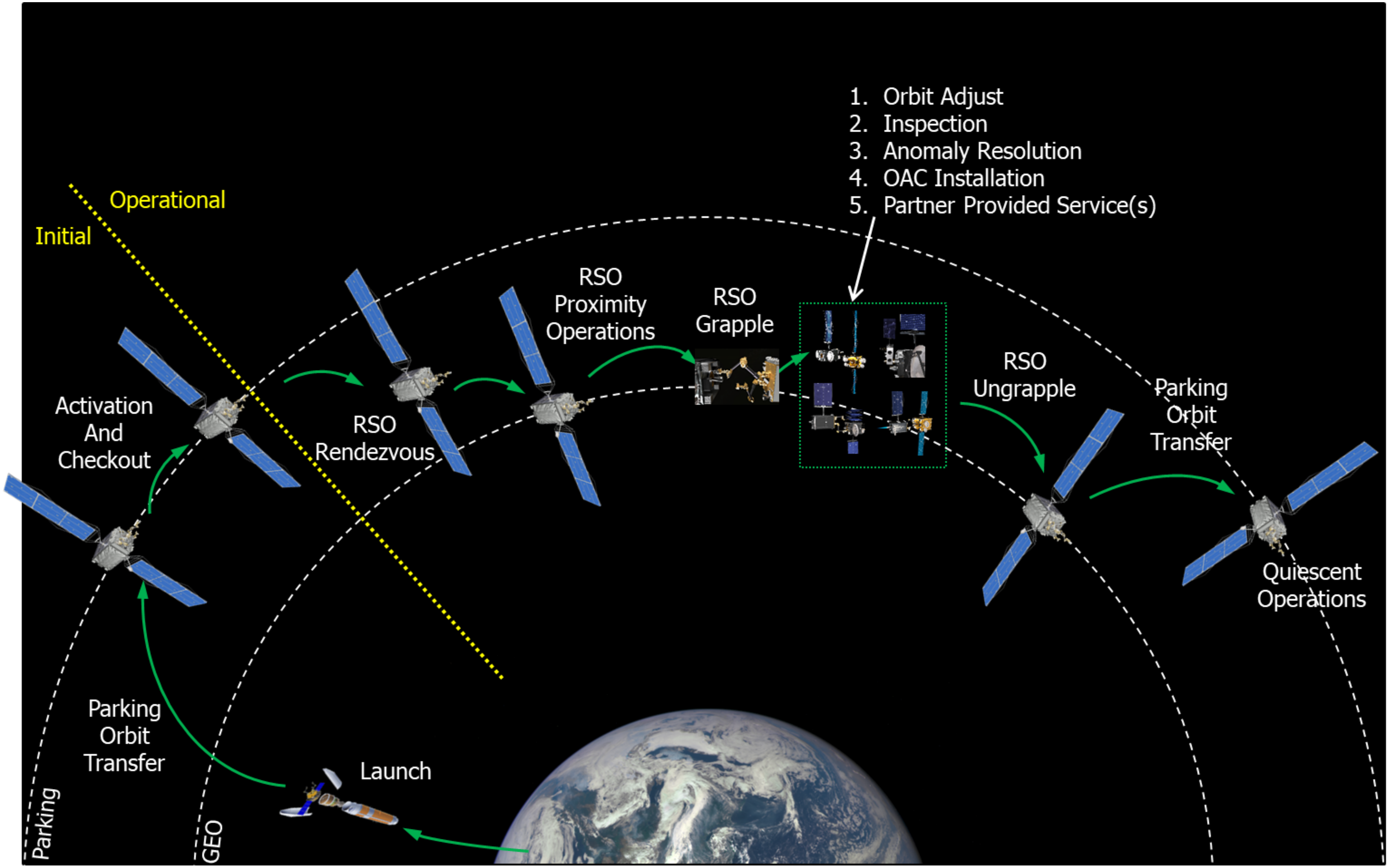


Cooperatively **correct** mechanical problems



Cooperatively **install** self contained payloads on-orbit

RSGS concept of operations



RSGS Phases:

Initial
- Launch
- Delivery to near GEO
- Activation & checkout
- Performance of DARPA capabilities
    - Inspect
    - Tug
    - Anomaly resolution
    - OAC

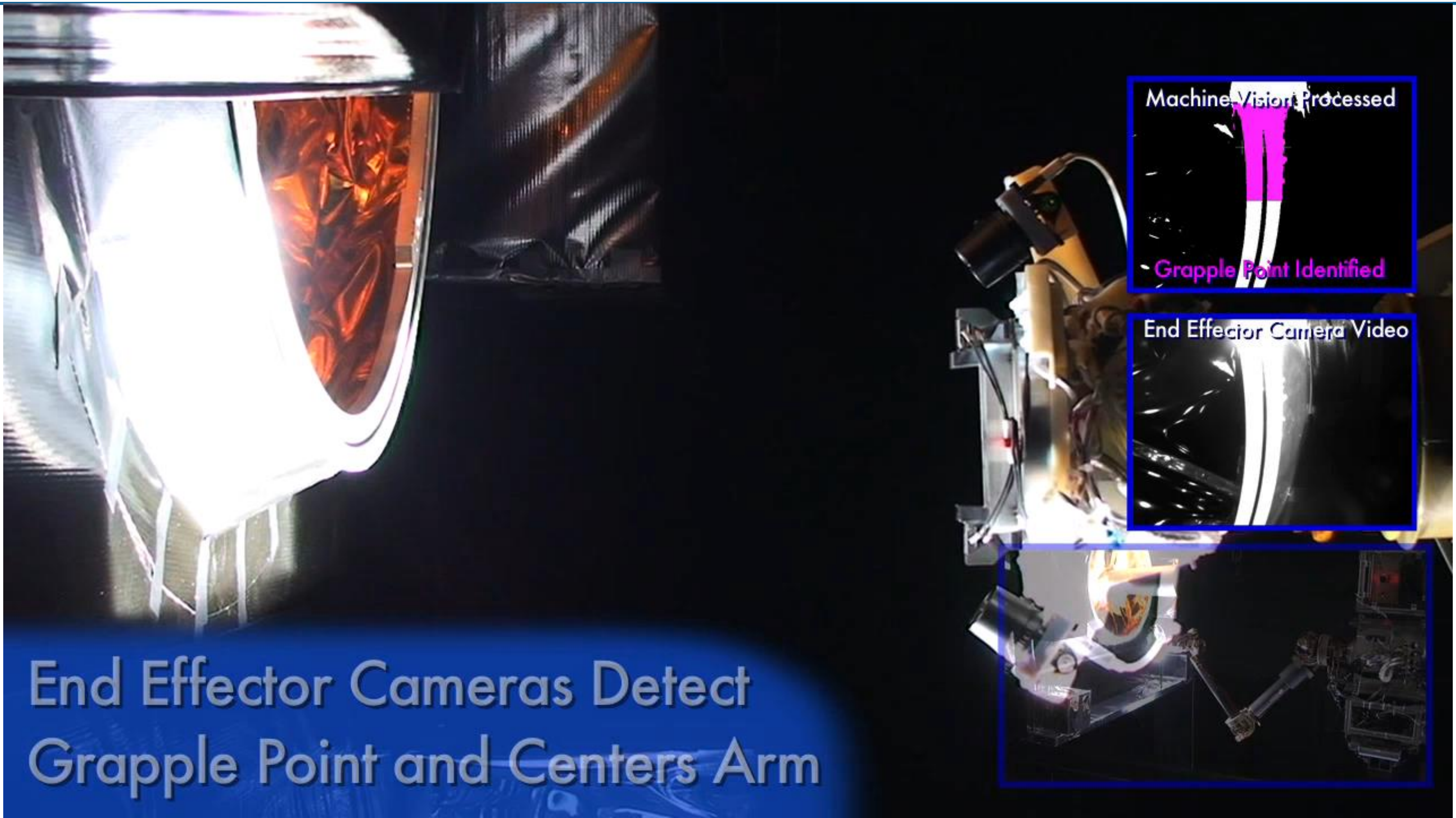
Operational
- Partner commercial activities
- Multiple clients per year
- POD retrievals

Refurbishment?

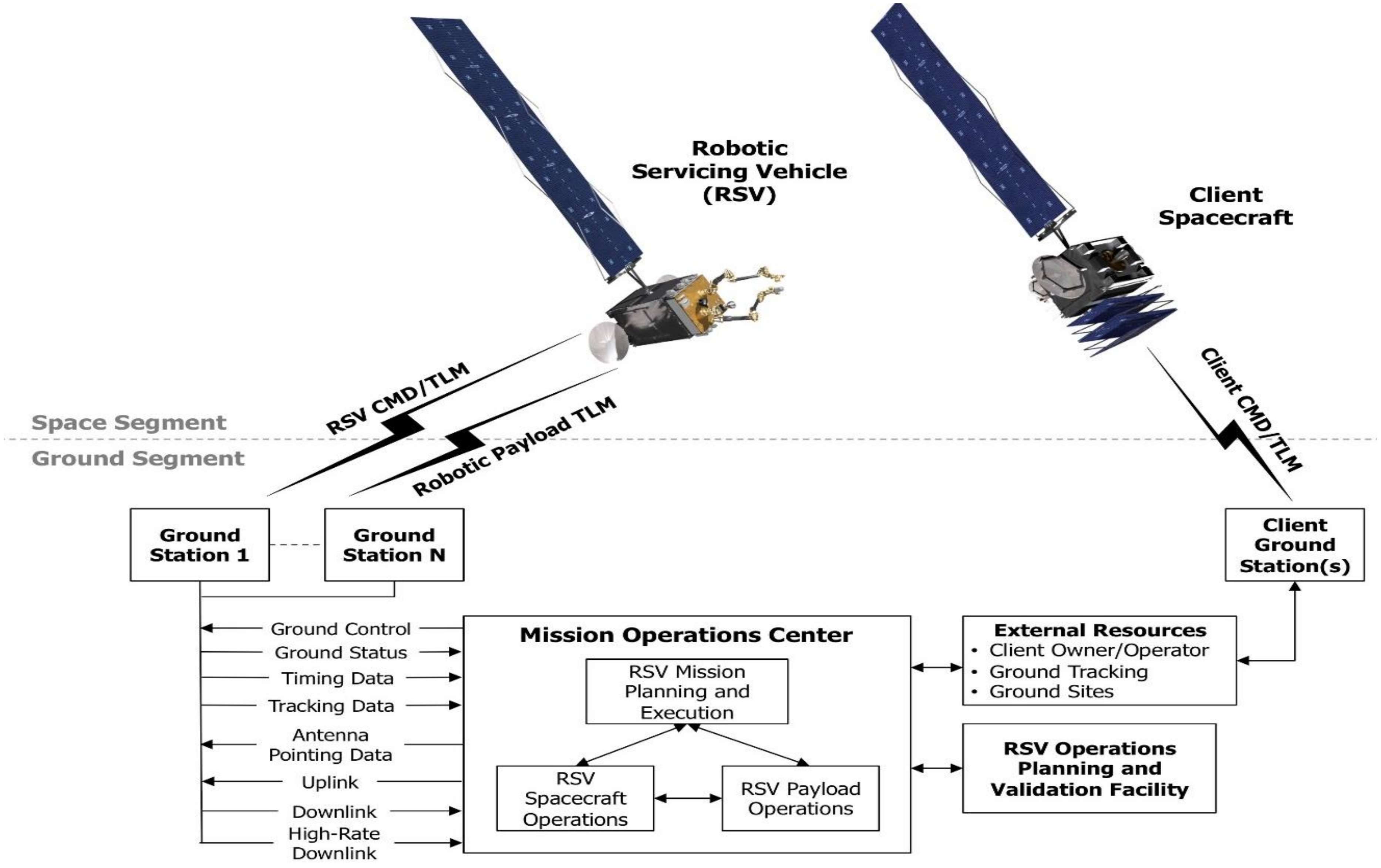
Retirement

RSGS concept animation

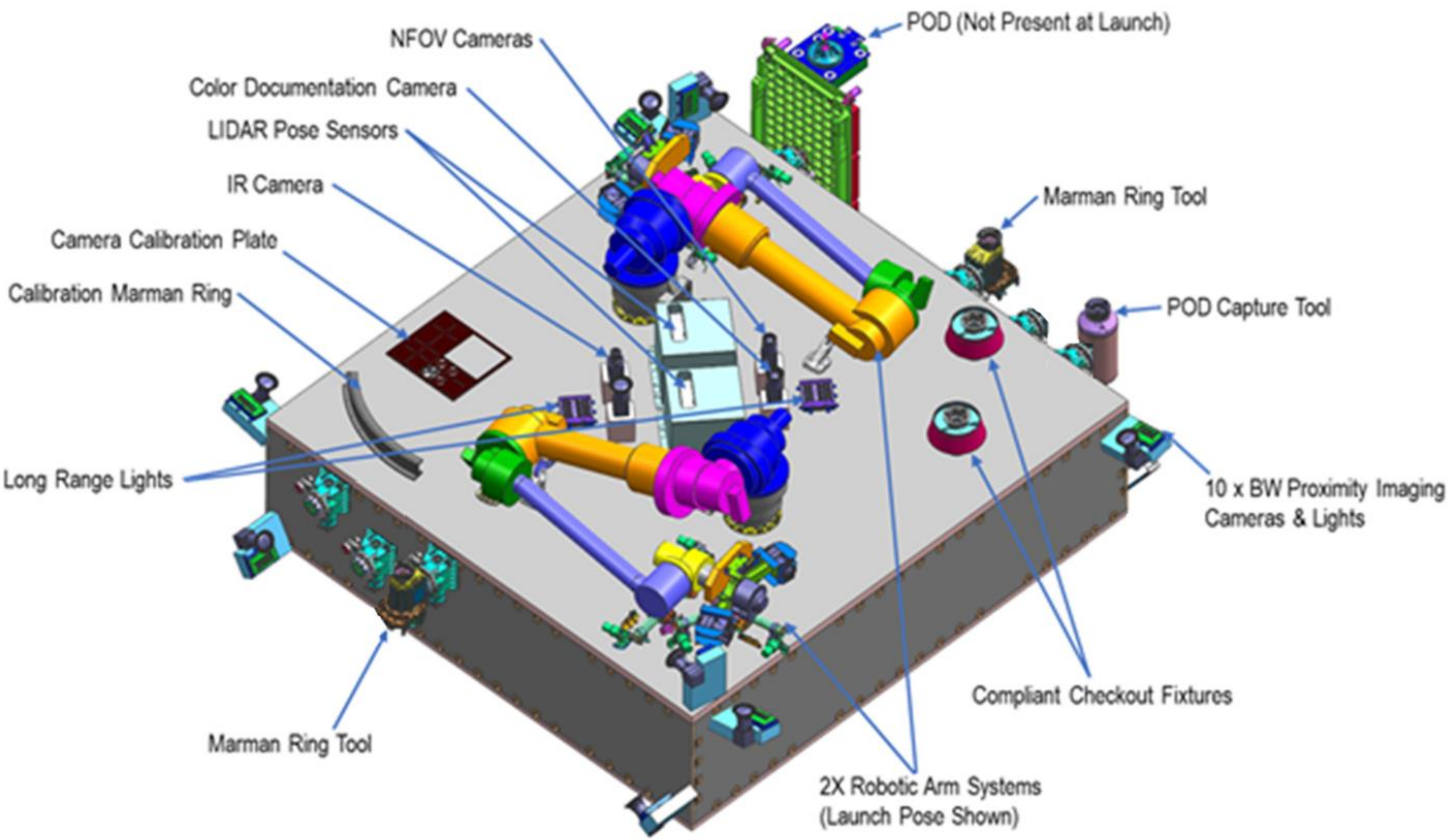
RSGS automated grapple



RSGS flight and ground system architecture

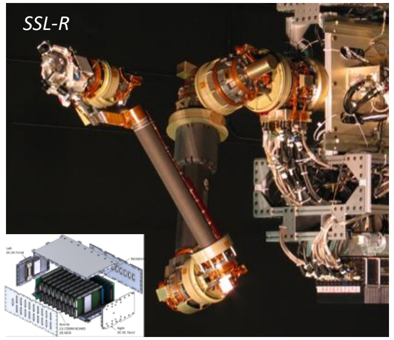


RSGS payload (layout notional)



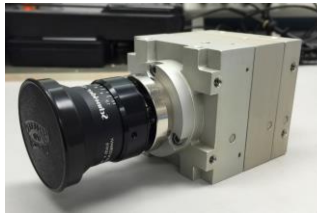
Dimensions shown here: 2.3m x 2.4m x 0.6m
(electronics deck not shown)

Payload Components

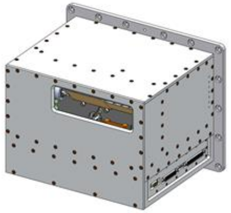


Robotic Arm Assembly
Post-CDR, Flight I&T in progress

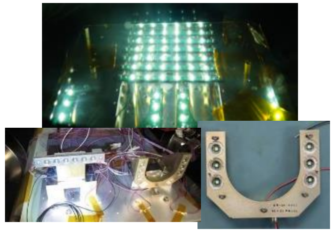
Oceaneering Space Systems
Tool Changer and Receptacle
Post-TRR, FM assembly and testing underway



Malin Space Systems
Panchromatic, Color, and IR Cameras
Post-MRR, EM testing underway, FM assembly in progress

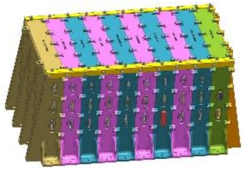


Neptec Design Group
LIDAR
Post-PDR, preliminary design in progress, long-lead parts procurement underway

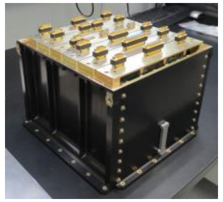


Payload Lighting
Post-CDR, EM testing underway, FM assembly in progress

End of Arm Control Board
Post-CDR, EM testing in progress, FM fabrication underway

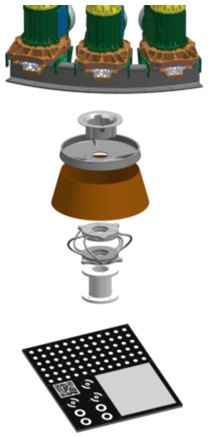


External Robotic Arm Control Electronics
Post-PDR, in FM design



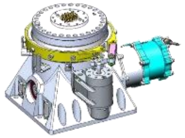
Power Distribution Unit
Post-CDR, EM testing in progress

Toolkit
Marman Ring Tool – post-PDR, EM integration in progress
POD Capture Tool – pre-PDR

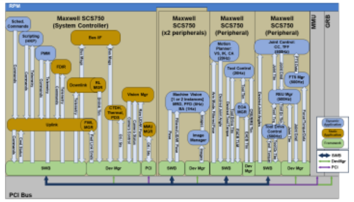


Calibration Suite
Post-PDR, EM design in progress

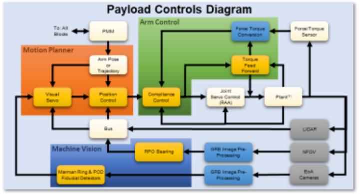
Robotics Processing Module and Common Remote Electronics
Post-CDR, EM assembly and testing underway



Sierra Nevada Corp
Structural, Power and Data Port
Post-PDR, in EM assembly



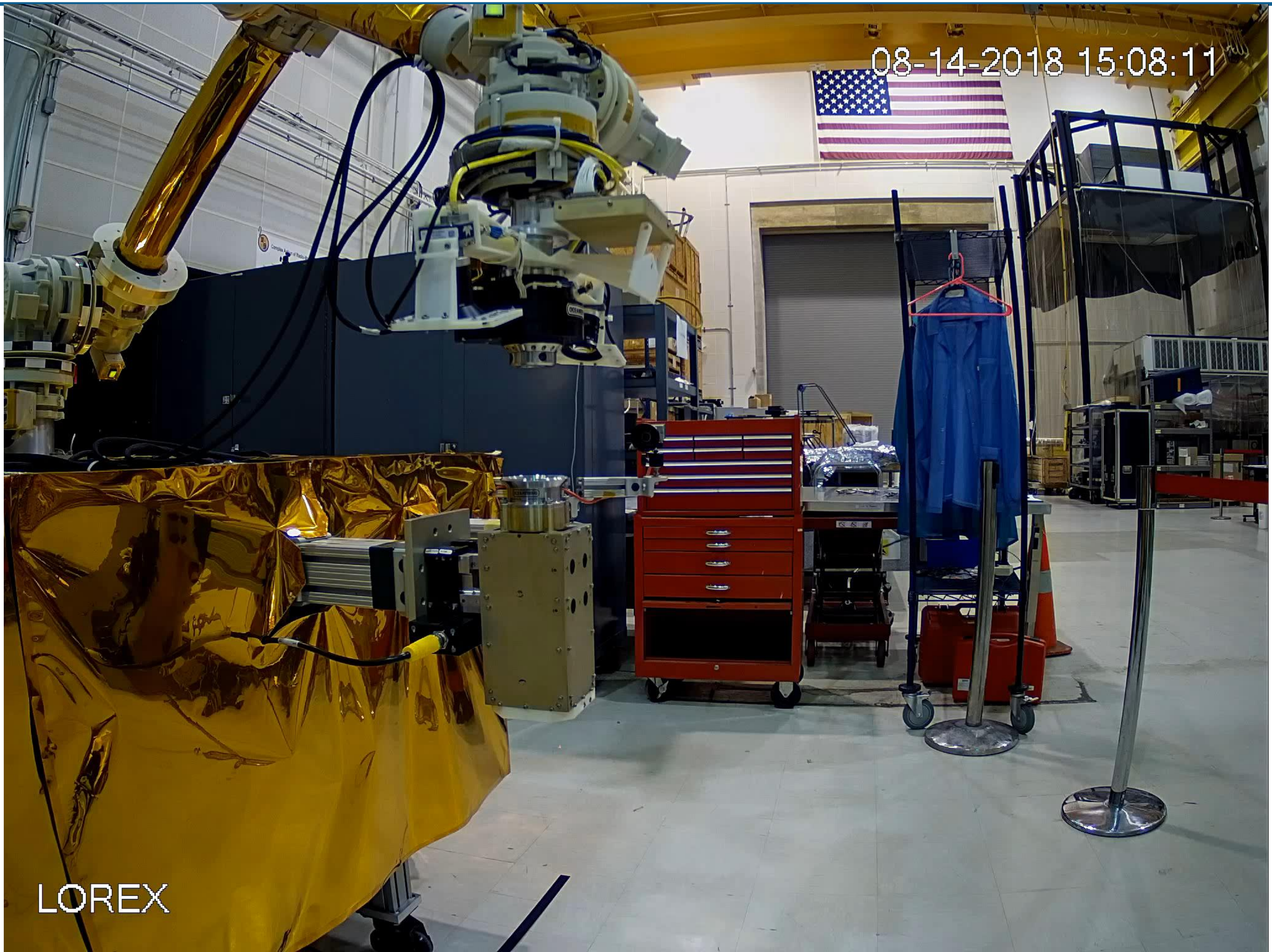
Payload Flight Software
Post-PDR, Build 3.4 pending release



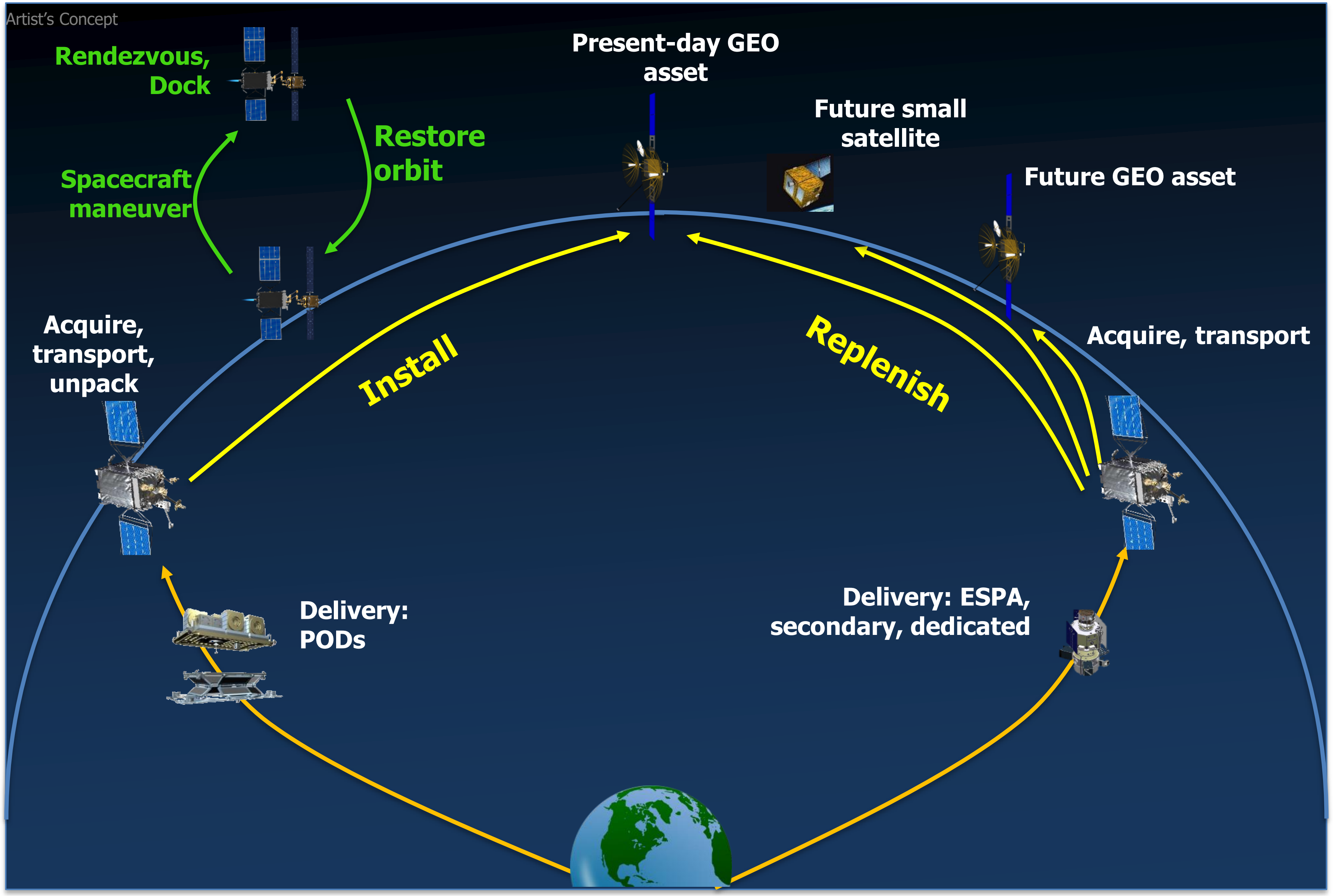
Payload Algorithms
Post-CDR, verification in process

Payload hardware and software FM assembly, integration, and testing is underway

RSGS tool changeout at NRL testbed

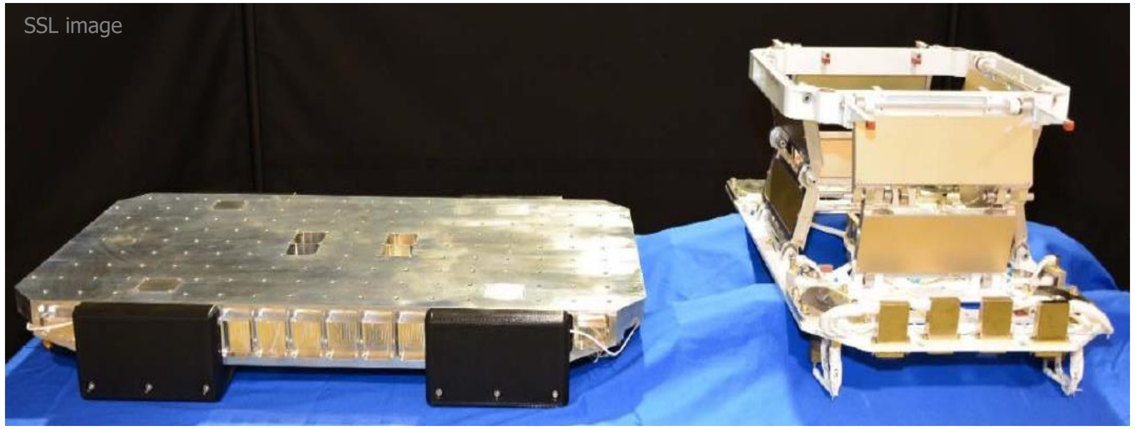


Vision: A servicing ecosystem in GEO

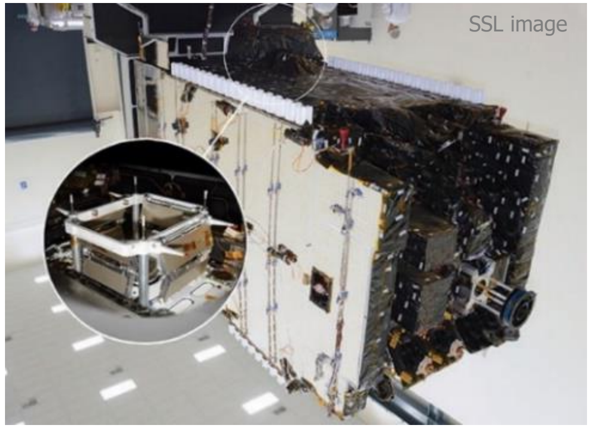


Related technologies: Payload Orbital Delivery (POD)

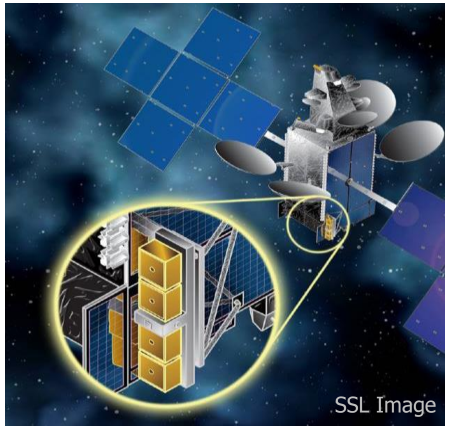
POD chassis and PEM



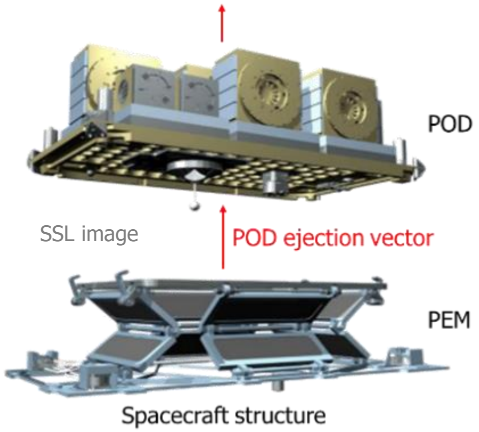
PEM on GEO bus



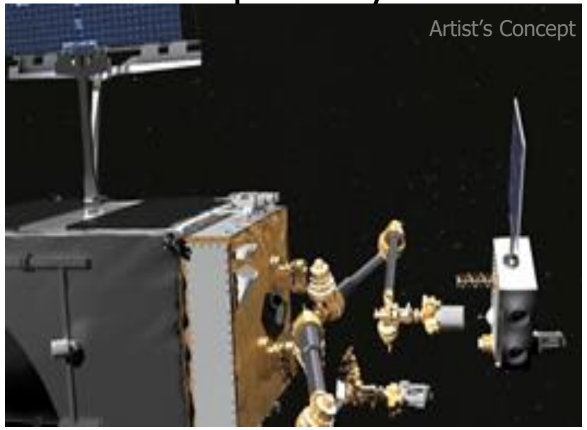
POD delivered to GEO
via host spacecraft



POD ejection



POD capture by RSGS

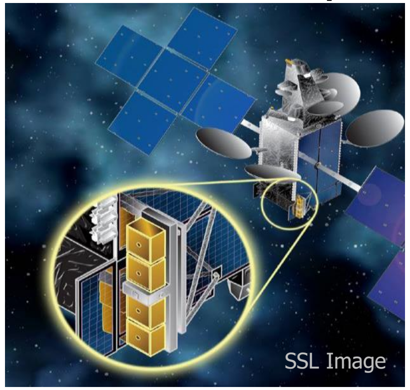


- Flight-releasable hosted payload
- Deliver logistics or OAC mass to GEO as **ridealong** on commercial client host spacecraft during their transit from launch to GEO
- **Flight proven** in 2018
- Concept applicable to any GEO spacecraft with available mass and volume

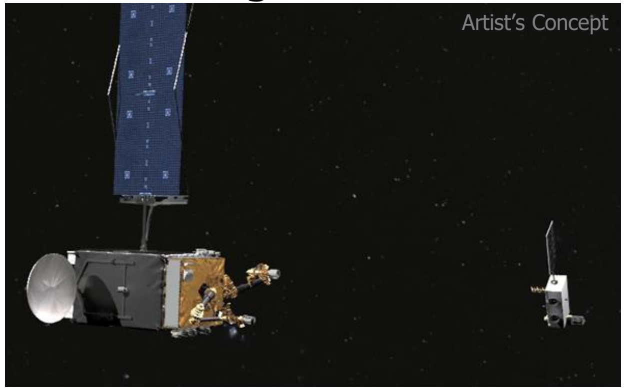
PODs enable recurring logistics route to GEO

Related technologies: On-orbit Attachable Capabilities (OAC)

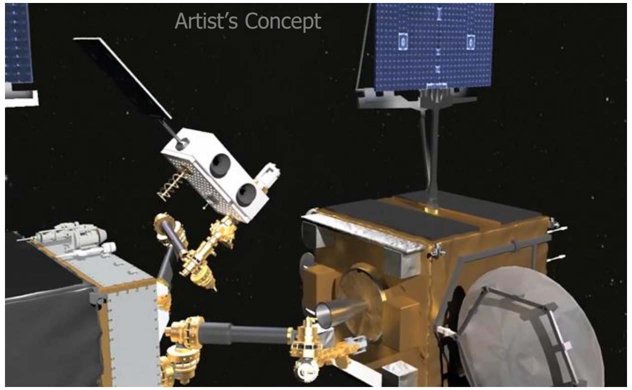
1) OAC delivered to GEO via POD system



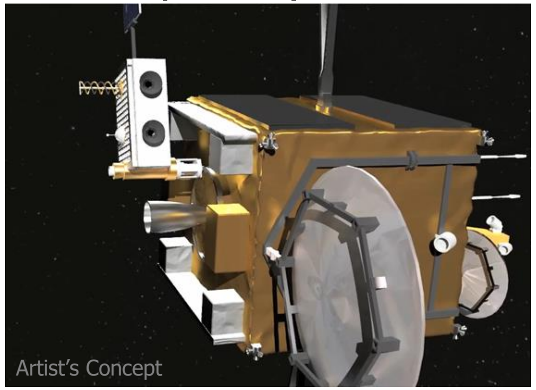
2) RSGS retrieves free floating OAC



3) RSGS installs OAC on client



4) Client with new capability



- Increased GEO fleet **resilience**
- New ability to modify satellites to meet **changing mission needs**
- Decouples hosted payload and spacecraft schedules
- New capabilities could lead to new "killer apps"
- On-orbit upgrade could lower cost of access to GEO
- Allows payloads that do not require propulsion or attitude control
- Effects on spacecraft design (on-orbit power/data ports, docking fiducial markings, etc.)

OACs enable space architecture adaptability

RSGS on-orbit animation (OAC installation)

Evolution: expanded capabilities, lower costs

LOGISTICS

CONSTRUCTION

First robotic capability in GEO

Artist's Concept

Artist's Concept

POD

Artist's Concept

OAC Capability

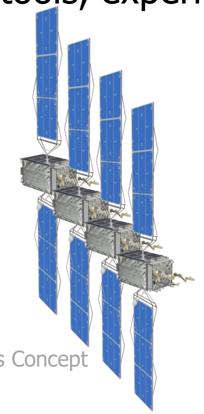
Fully automated space logistics

First steps in GEO logistics

REPAIR ◆ *REPOSITION* ◆ *INSPECT* ◆ *AUGMENT*

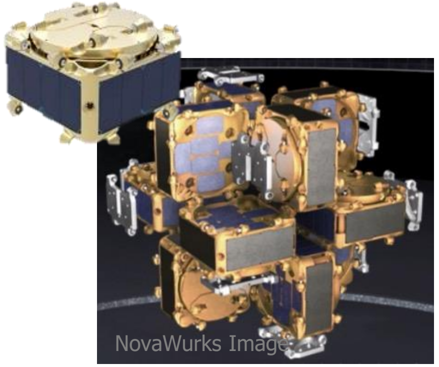
Technology development and investment

Expanded coverage, new tools, experiments

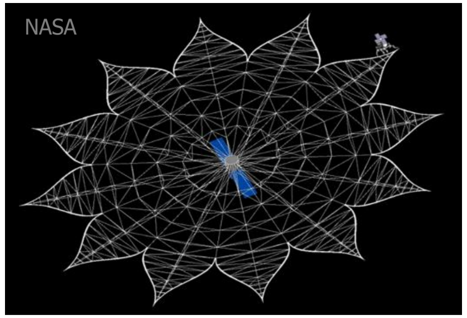


Artist's Concept

Modular spacecraft with on-orbit replaceable units



Large apertures, structures, and bases



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Naval Research Laboratory

Advancing research further than you can imagine

Spacecraft Engineering Division

Naval Center For Space Technology (NCST)

An Overview

Dr. Gurpartap "GP" Sandhoo, SES
Superintendent, Spacecraft Engineering Dept. (Code 8200)
(202) 404-2701 / gp.sandhoo@nrl.navy.mil

Established July 2, 1923 - 95 Years of Innovation

"The Government should maintain a great research laboratory to develop guns, new explosives, and all the technique of military and naval progression without any vast expense."

– Thomas Edison, 1915

"One of the imperative needs … is machinery and facilities for utilizing the natural inventive genius of Americans to meet the new conditions of warfare."

– Josephus Daniels, Secretary of the Navy, 1915

Naval Research Enterprise

Chief of Naval Research
& OPNAV N94

RADM David Hahn, USN

Vice Chief of Naval Research &
CG, Marine Corps Warfighting Lab

BGen Christian Wortman, USMC

Organization … 18 Research Divisions... $1.3 Billion Executed

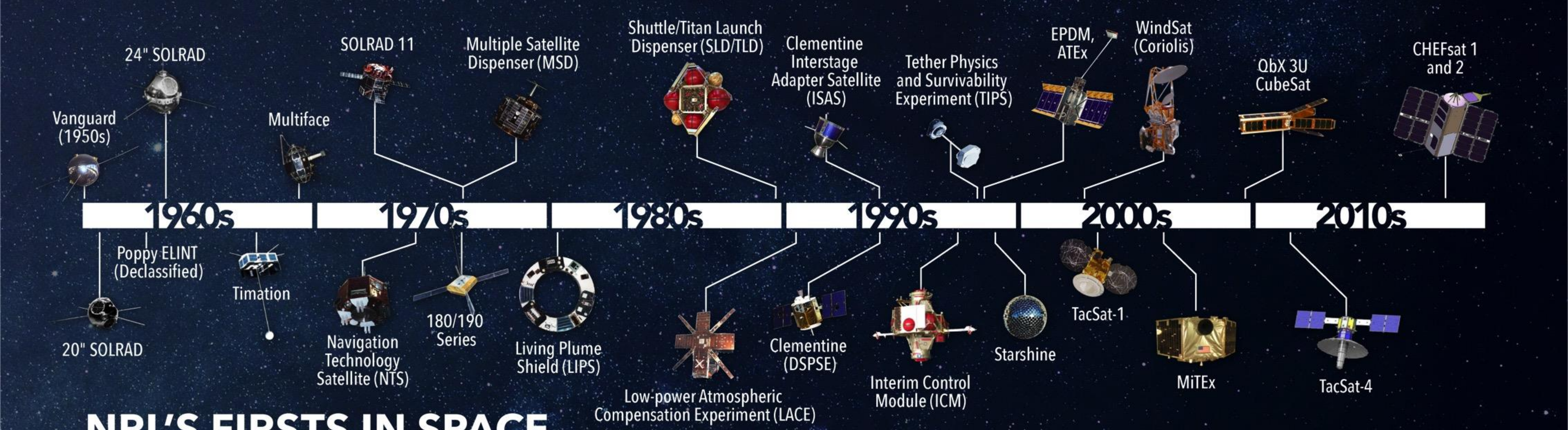
Dr. Bruce Danly
Director of Research

Executive Leadership

CAPT Scott Moran
Commanding Officer

Business Operations	Systems	Materials Science & Component Technology	Ocean & Atmosphere Science & Technology	Naval Center for Space Technology
• Contracting • Financial Management • Supply • R&D Services	• Radar • Information Technology • Optical Sciences • Tactical Electronic Warfare	• Computational Physics & Fluid Dynamics • Chemistry • Materials S&T • Plasma Physics • Electronics S&T • Biomolecular Science & Engineering	• Acoustics • Remote Sensing • Oceanography • Marine Geosciences • Marine Meteorology • Space Science	• Space Systems • Spacecraft Engineering

Naval Center for Space Technology: Developing New Capabilities with Operational Impacts



NRL'S FIRSTS IN SPACE

A HISTORY OF ADVANCED TECHNOLOGY TRANSITIONS TO OPERATIONS AND INDUSTRY.

- 1st Satellite Control Ground Station (Blossom Point, 1956)
- 1st Earth Observing/Weather Satellite (Vanguard 2, 1959)
- 1st U.S. Recon Satellite (GRAB, 1960)
- 1st Multiple Satellite Launch (Solrad 1, 1960)
- 1st Space Object Tracking System (Naval Space Surveillance System, 1961) Transferred to U.S. Air Force Space Command in 2004
- 1st U.S. ELINT System (POPPY, 1962-1977)
- 1st Observatory on the Moon (Far UV Camera on Apollo 16, 1972)
- 1st Timing and Navigation Satellites (TIMATION and NTS Series, 1964-1977) Became NAVSTAR GPS
- 1st Tactical Broadcast From Space (LiPS Series, 1980s) Evolved Into TADIXS-B and IBS
- 1st Full Lunar Mapping, and Water Ice Detection (Clementine, 1994)
- 1st Ocean Wind Vectors Obtained Passively From Space (WindSat, 2003)
- 1st Operationally Responsive Space (ORS) Satellite (TacSat-1, 2004)
- 1st to Fly Many Enabling Components Such as Solar Cells and Atomic Clocks, Cold Gas Thrusters, Onboard Data Storage, 3 Axis Stabilization, Rechargeable NiCad Batteries

NRL_Sat_Launch_Timeline_2018-v5

Theory without practice is intellectual play, practice without theory is blind

NCST’s Satellite Operations Enterprise – Spacecraft Operations, Mission Operations

- VMOC provides a single aggregation point for mission tasking, processing, and display
- Neptune software’s common baseline, showcased at Blossom Point Tracking Facility (BPTF) with common ground hardware resources, enables a resilient and flexible, spacecraft C2 architecture
- OCEAN provides precision orbit determination and propagation for ground operations and mission planning
- Blossom Point provides extensive RF connectivity and, using Neptune software, is highly automated

Mission Operations Center (MOC)

- Web-based mission planning and scheduling support system
- Provides:
  - Satellite modeling
  - Tasking and scheduling
  - User requests
  - Maneuver planning
- Government owned

Satellite Operations Center (SOC)

- C2 software used for satellite development, integration, test, launch, and operations
- OCEAN is used to provide accurate ephemeris prediction to mission and ground operations
- Government owned

Ground Station

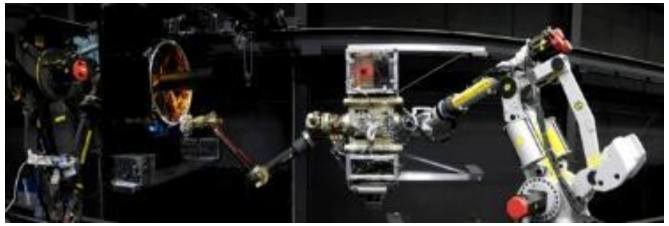
- Provides:
  - Dedicated antennas
  - Advanced automation
  - Tracking
  - Data acquisition

Data Processing

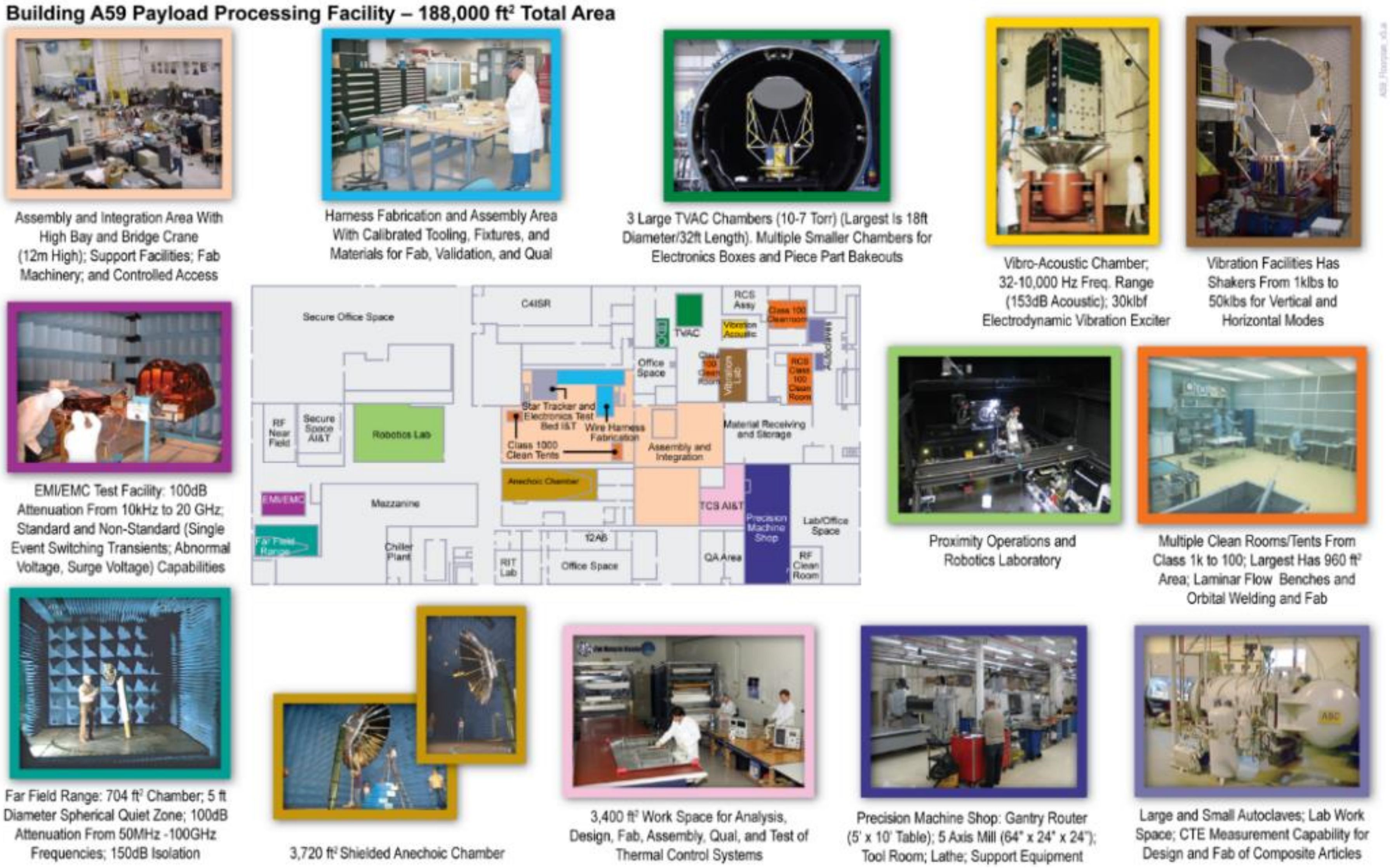
- Data processing is performed on a mission-specific basis
- Examples:
  - Big Data
  - S2A

VMOC, Neptune, OCEAN, and BPTF provide a capable, well-integrated solution to many mission needs

Spacecraft/Space Vehicle/Payload- End to End Conceive, Design, Build, Integrate, Assemble & Test



Coming Soon

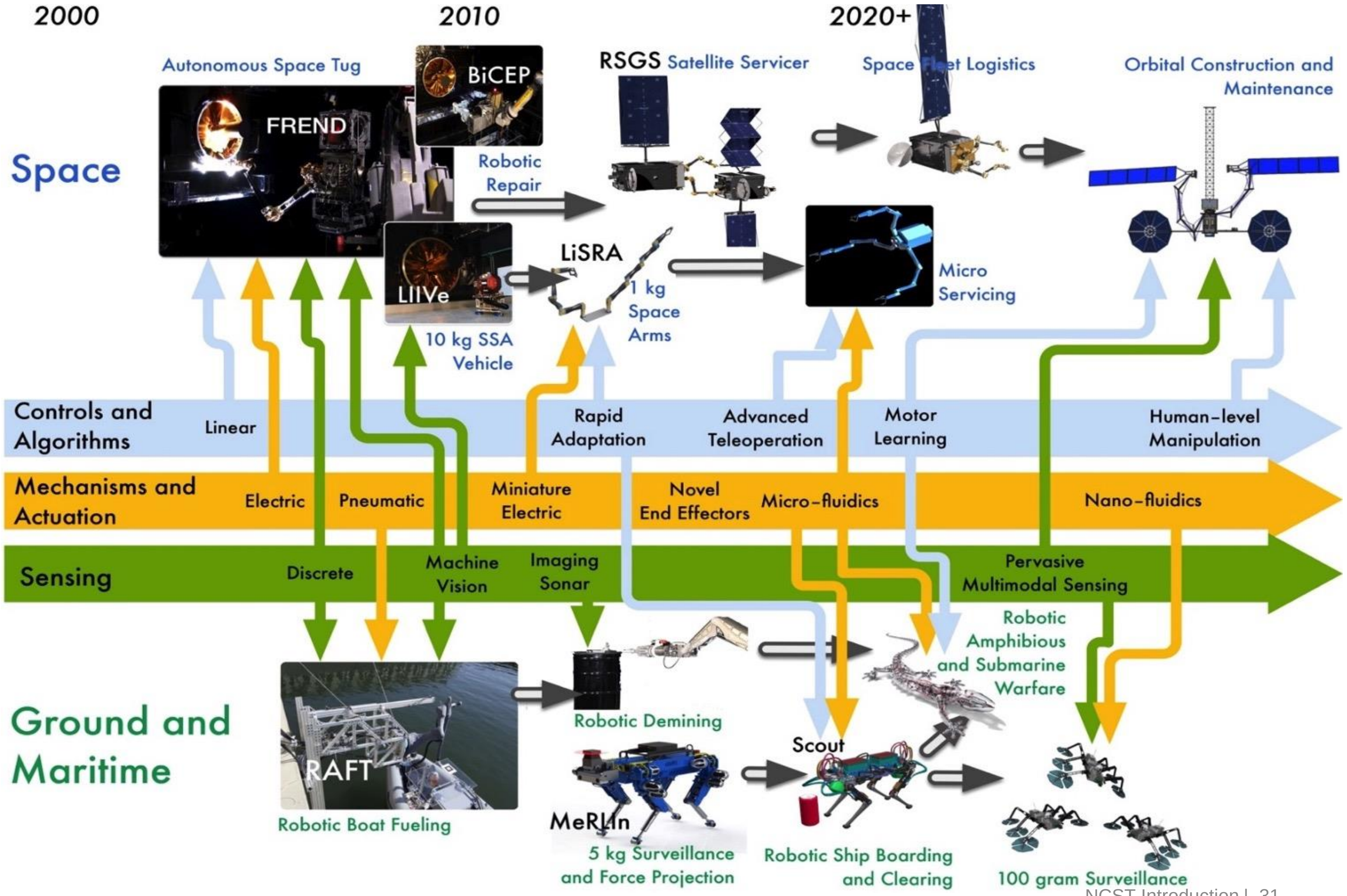


Robotic's Vision of Transformation

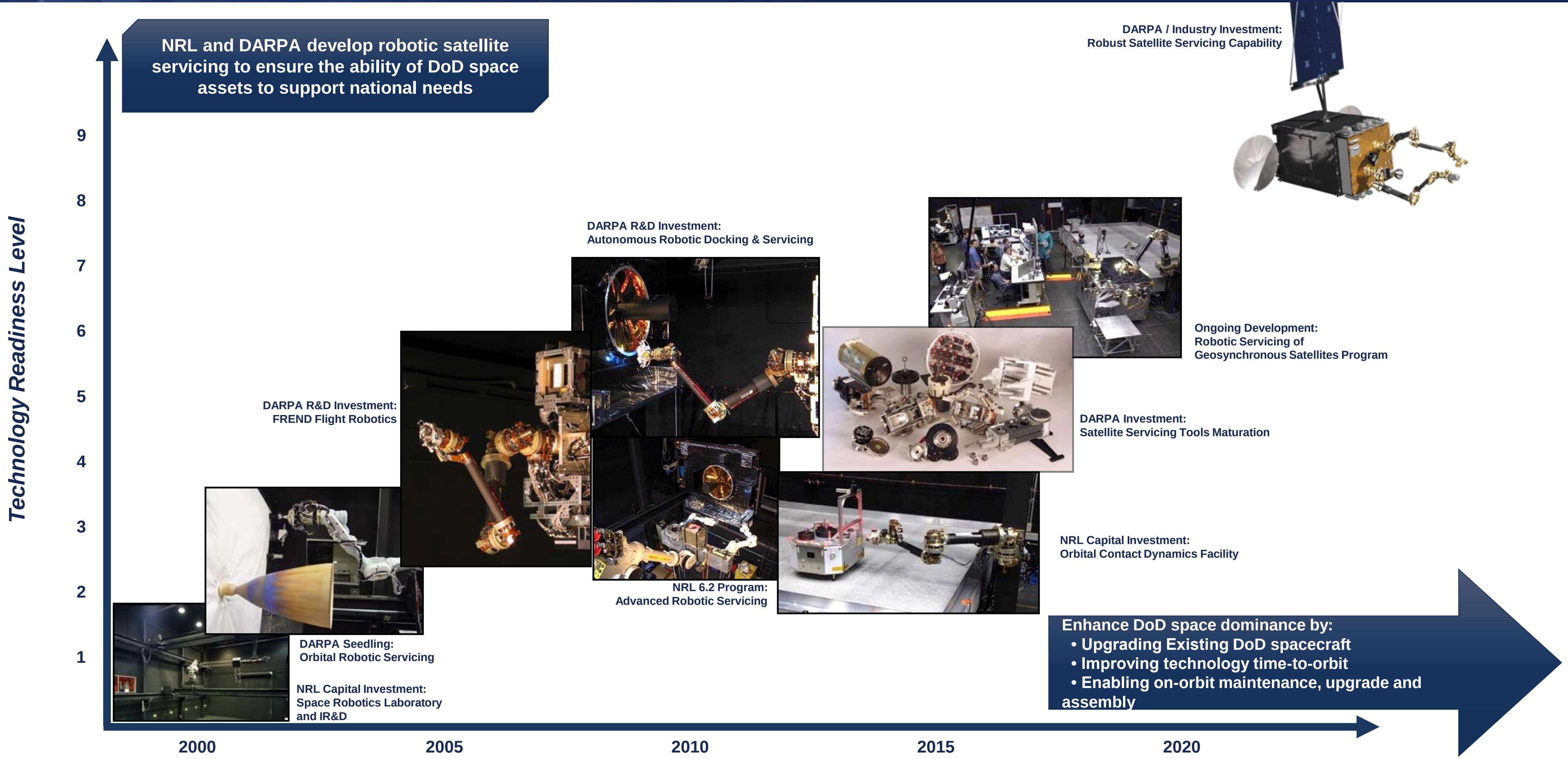
Decades of NRL robotics research have generated significant space, ground, and maritime innovations

Significant internal investments in facilities, personnel, and research, combined with strong external sponsor partnerships

Transformational robotics technology will have a lasting impact on our nation

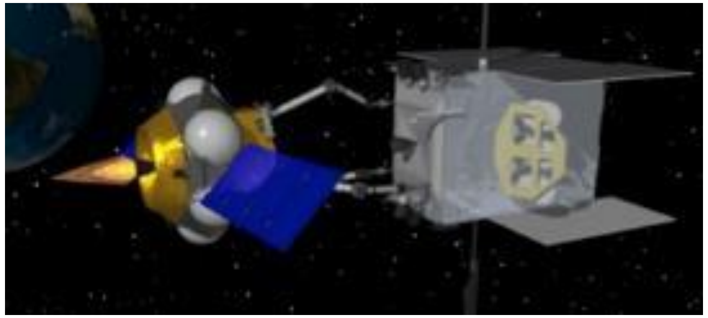


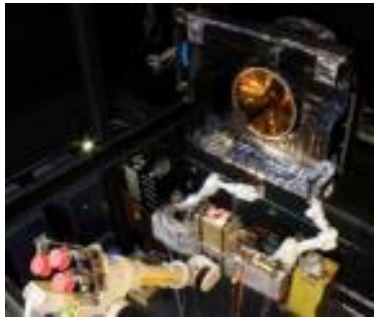
Space Robotics Technology Maturation



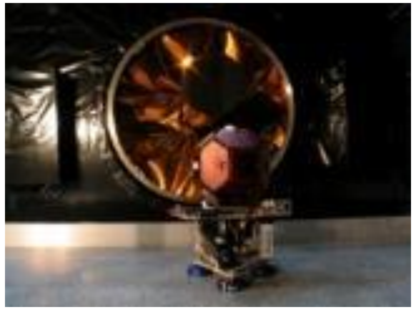
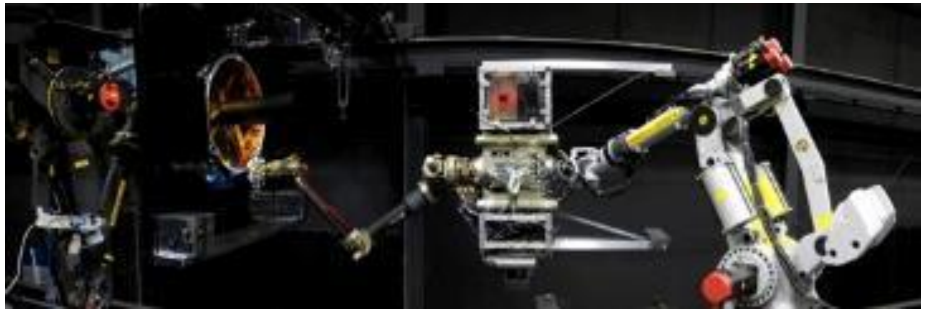
DoD Center of Excellence for Space Robotics

- Significant NRL internal investments in facilities, people, and research applying to long-range goals since the late 1990s
- Leading national efforts in developing new space robotics capabilities and policy
- Nationally unique capabilities in robotic control algorithms and software, innovative mechanism design, systems engineering, and system testing and validation
- NRL robotics has attracted external funding from DARPA (RSGS), USAF, NASA, and Industry





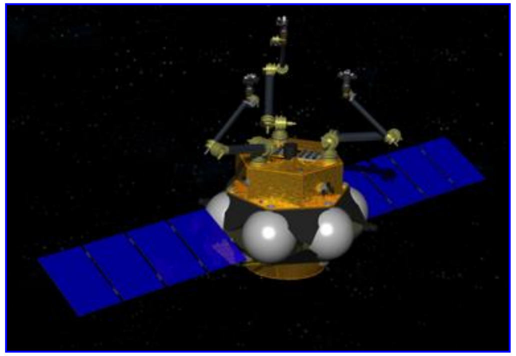


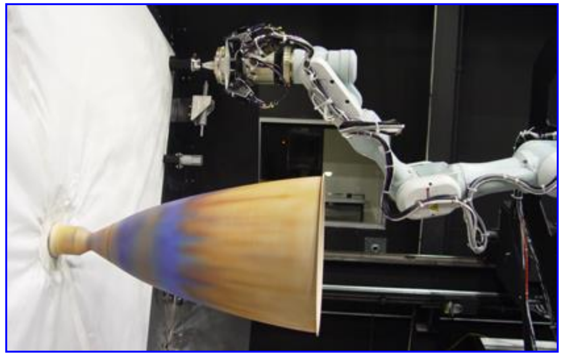
U.S. NAVAL RESEARCH LABORATORY

NRL / DARPA Space Robotics History

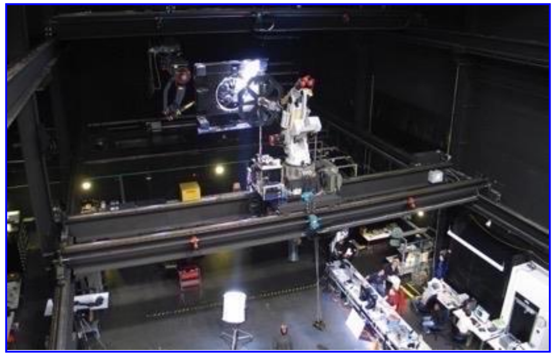
DARPA



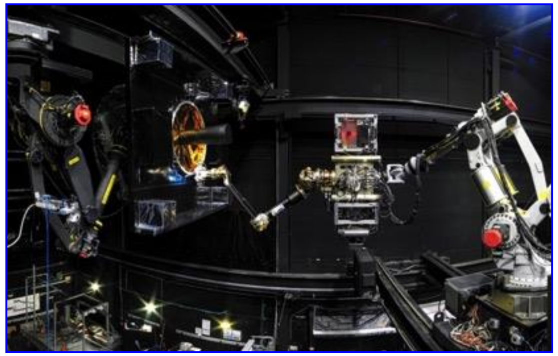
2004: SUMO Point Design



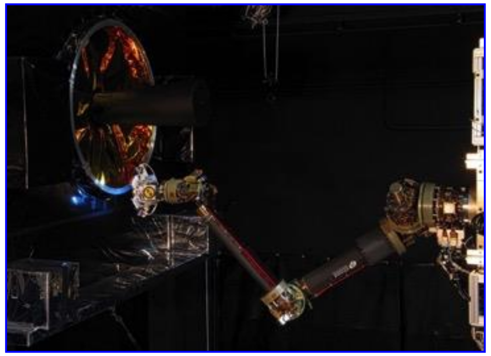
2004: SUMO Grapple Demonstration



2005: SUMO RPO & Grapple Demonstration



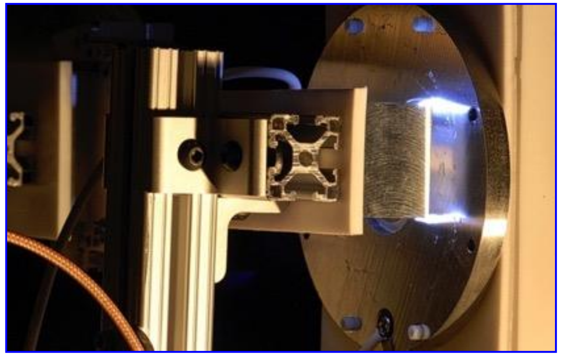
2008: FREND EDU Grapple Demonstration



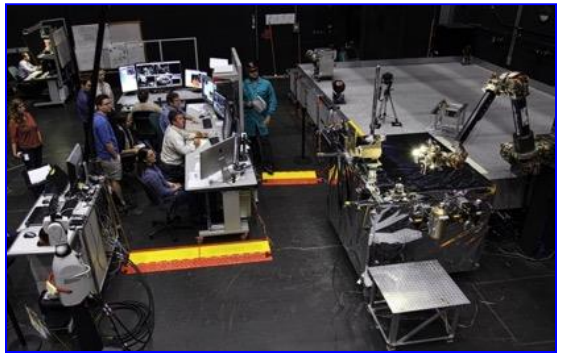
2008: FREND Flight Prototype Grapple

2009: FREND Environmental Testing

2013: Phoenix EMI Testing



2013: Phoenix First Contact Discharge R&D



2014: Phoenix Teleoperations Tool Testing

NRL / DARPA Space Robotics History

- RSGS is benefiting from multiple past DARPA programs with substantial technology development performed at NRL.

- The core focus of the technology development has been maturing elements of robotic servicing for government and commercial missions:
  - 2002-2005 – SUMO: Spacecraft for the Universal Modification of Orbits
  - 2005-2009 – FREND: Front-end Robotics Enabling Near-term Demonstration
  - 2009-2010 – FREND Application Studies
  - 2010-2011 – MGS: Manned Geo Servicing Study, joint study by DARPA/NASA
  - 2011-2013 – Phoenix
  - 2014-2015 – Phoenix (GEO Robotics)
  - 2015-… – Robotic Servicing of Geosynchronous Satellites (RSGS)

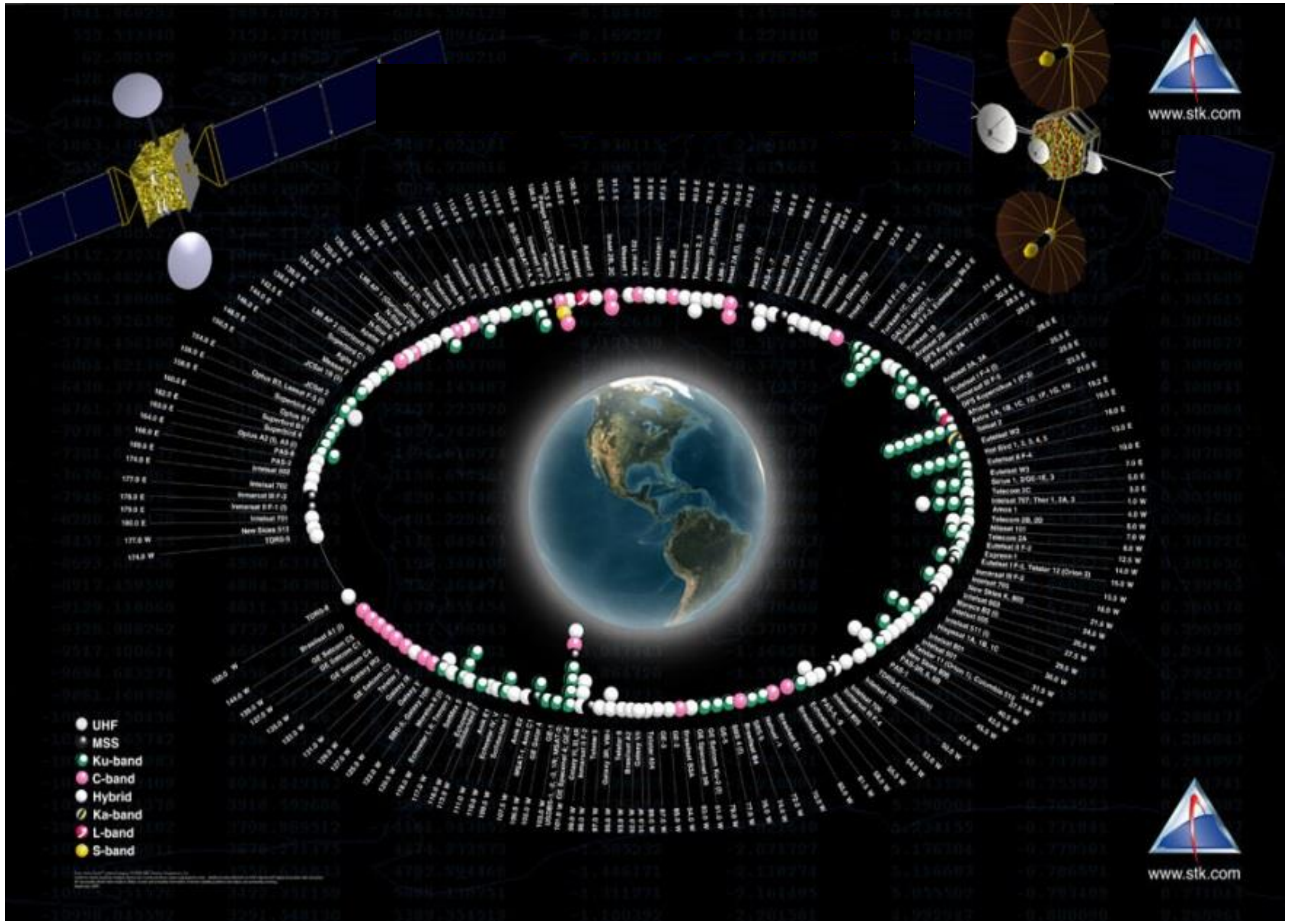
- Focus throughout has been:
  - Systems engineering to identify where development is needed to enable robotic servicing as a national capability
  - Risk reduction and technology development to mature capability
  - Robust laboratory testing to validate technologies and system integration

RSGS Partnership Goals

Joseph Parrish
RSGS Program Manager

May 22, 2019

Why DARPA chose a public-private partnership structure for RSGS



Why GEO?
Large concentration of serviceable, accessible assets

Why commercial?
~5:1 commercial to government

→ More data
→ Reduced cost
→ Available for government when needed

Why not DARPA-only?
We focus on establishing new capabilities, not on operating them

Ongoing commercial enterprise enables long term US servicing presence in GEO

RSGS Program Solicitation recap

- Soliciting Other Transaction (OT) proposals under the authority of 10 USC § 2371b for a public-private partnership

- Commercial partner team would be a U.S. space industry builder-owner-operator
  - Provide a GEO-qualified bus (modified as needed to accommodate robotic payload)
  - Integrate the robotic payload to the bus, creating the Robotic Servicing Vehicle (RSV)
  - Launch the RSV to GTO or GEO on partner-provided U.S.-manufactured launch vehicle
  - Provide mission operations and ground communications across the GEO belt
  - After DARPA-specified on-orbit checkout/demo period, operate the RSV commercially for several years to service many government and commercial clients

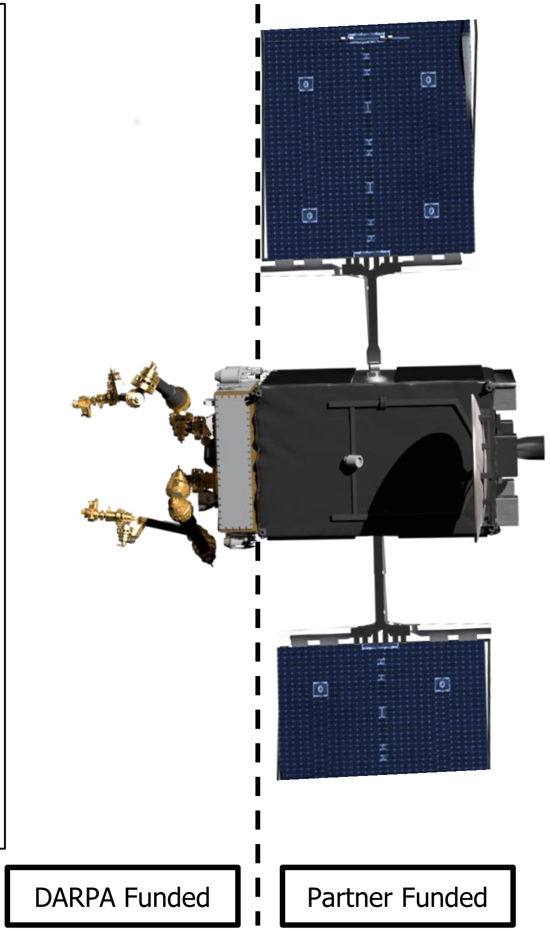
- End state is a U.S. commercially-owned and -operated RSV in GEO, carrying the Government-furnished robotic payload

RSGS partnership responsibilities

DARPA

Government Partner for RSGS

- Program management and technical oversight
- Robotic payload
  - Program management & system engineering
  - Robotic arms, tools, sensors
  - Integration and test, V&V
- Robotic ground control workstation
- Robotic mission operations planning and training



Partner

Commercial Partner for RSGS

- Program management and mission system engineering
- Spacecraft bus (heritage GEO bus, tailored for RSGS requirements)
- Integration and test
- Launch vehicle procurement
- Launch vehicle integration
- Mission control center for operations
- Servicing mission execution

RSGS program phases

- Spacecraft and payload development
  - Government-funded robotic payload development already underway (post-Payload PDR with numerous long-lead flight articles already in production)
  - Partner to commence spacecraft bus development soon after selection
- Integration and launch
  - Partner to integrate payload to spacecraft bus => RSV
  - Partner to integrate RSV to launch vehicle
  - Partner to launch RSV to GTO or GEO
- Capability demonstration
  - Partner-performed, Government-directed on-orbit checkout and demonstration using Government-arranged client(s)
- Commercial operations
  - Partner-operated servicing of Government and commercial clients

Notional RSGS program schedule

The following schedule dates are notional, subject to negotiation between the Government and Partner:

- Payload Critical Design Review (CDR) – Q1FY20
- Bus System Requirements Review (SRR) – Q3FY20
- Bus Preliminary Design Review (PDR) – Q1FY21
- Bus CDR – Q3FY21
- Payload Delivery – Q1FY22
- Bus Delivery – Q1FY22
- IRW Delivery – Q1FY22
- Ground System Readiness Review – Q2FY22
- RSV I&T Complete – Q3FY22

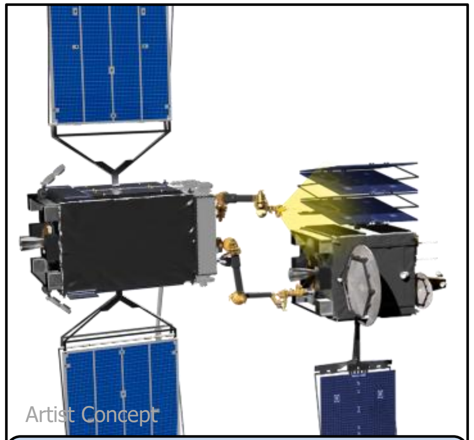
Proposer should provide a schedule that fits their partnership concept

Funding and consideration

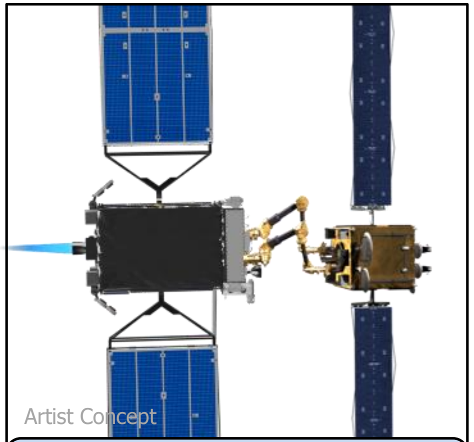
- The Government expects to transfer no funding to the Partner
- The Government-funded robotic payload will eventually be owned by the Partner (after the demonstration period)
- The Partner must offer the Government consideration in exchange for the robotic payload
- Some examples of consideration
  - Assured pricing for future missions to service Government clients
  - Agreement to perform robotic experiments for Government clients
  - Provision of operational data and lessons learned from servicing operations
  - Training of Government personnel
  - Other offers consistent with the Partner’s business case
- The total amount of consideration will be a factor in the evaluation of Partner proposals

Let's get this done!

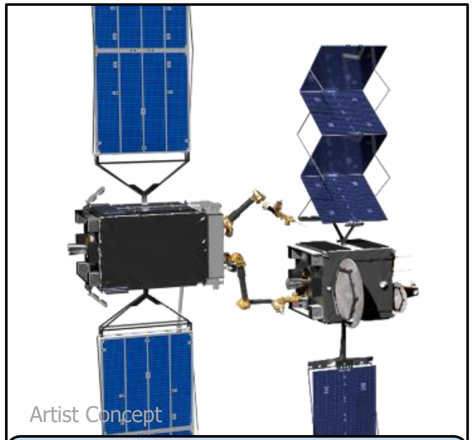
- We've shared what we want to get done on-orbit and why
- We're looking forward to hearing your ideas for what we can do together
- Let's work together to make a new reality in space



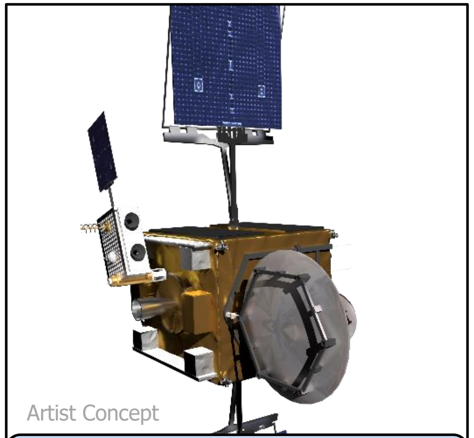
Cooperatively **inspect** spacecraft experiencing anomalies



Cooperatively **assist** with orbit adjustments



Cooperatively **correct** mechanical problems



Cooperatively **install** self contained payloads on-orbit

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Program Solicitation
DARPA-PS-19-01

Chris Glista

DARPA Contracts Management Office

May 22, 2019

DISCLAIMER

If the Program Solicitation contradicts any information in these slides,

the <u>Program Solicitation</u> takes precedence.

DARPA RSGS Award Process

Agenda

- Other Transaction Agreement / Program Solicitation
  - What is it
  - Why are we using it
- Program Goals and Evaluation Criteria
  - Evaluation areas
  - Partnership
- Step-by-Step Solicitation Process

Other Transaction (OT) Agreement/Program Solicitation

The Government intends to award a single OT agreement to the offeror whose proposal is determined to be the most advantageous to the Government.

What is it?

- OT is awarded under the authority of 10 U.S.C. § 2371b
- Program solicitation is OT acquisition method
- Non FAR/DFARS based award – e.g. not required to follow Government accounting rules
- OT intended to reflect commercial agreements

Why?

RSGS partnership is a unique method – OT agreements give the parties the freedom to approach this in a more commercial-like manner.

Program Goals and Evaluation Criteria

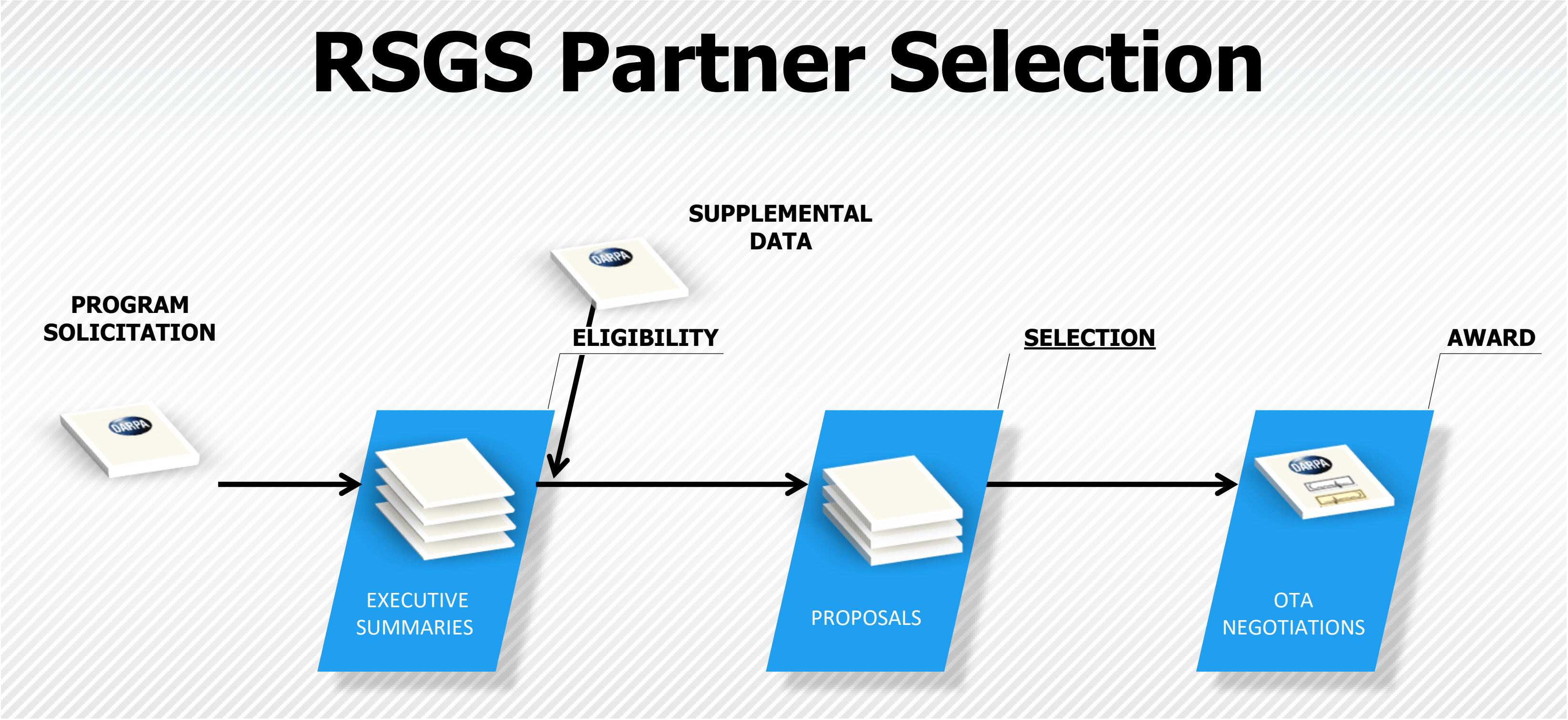
Evaluation areas

- Technical – Can your team technically perform?
- Business – Not only can your team financially manage, but will your team successfully transition this effort into a persistent servicing capability, and does your team have the financial capability and corporate commitment?
- Consideration – What consideration will be given to the government for the GFE and services?
- No Traditional Cost Evaluation

Partnership

- Partner team must include a bus manufacturer and the ultimate robotic servicing satellite owner/operator (which may be the same or different commercial entities)

Step-by-Step Partner Selection



Three Step Partnership Selection Process

Step 1 – Executive Summary / Eligibility

Step 2 – Proposal Submission / Evaluation / Selection

Step 3 – OT Negotiations / Award

Notes on Submissions

- DARPA will receive unclassified submissions via its web-based upload system. Submission must be in a single zip file not exceeding 50 MB.
- DO NOT include any classified information in the unclassified portion of the submission or it may be deemed non conforming. Follow the appropriate classified submission method as indicated in the program solicitation
- DO NOT wait until the last minute to make submissions – the submission deadlines as outlined in the program solicitation or in subsequent proposal submission instructions will be strictly enforced!
- DO NOT forget to FINALIZE your submission in the submission tool! Failure to finalize will prevent the Government from proper receipt.

Proposal structure

Proposal Summary (15 page limit)

Volume 1: Technical Description (75 pages)

T1) System Concept and Summary of Performance

T2) Mission Compatibility and Performance Analysis

T3) Development

T4) Manufacturing

T5) Bus to Payload Integration

T6) Test and Verification

T7) RSV to Launch Vehicle Integration

T8) Launch and Delivery to GEO

T9) Ground Segment Approach and Operator Certification

T10) Technical Risks

T11) Safety and Mission Assurance

T12) Compliance with Evaluation Criteria

Volume 2: Business & Management Plan (110 pages)

B1) Organization Information

A. Business Strategy
B. Market
C. Products and Services
D. Marketing and Sales
E. Governance Structure
F. Management Team
G. Finance

B2) RSGS Development and Demonstration Plan

A. Plan and Schedule
B. Resources
C. Teaming Arrangements
D. Performance Milestones
E. Consideration to Government

B3) RSGS Operational Readiness Plan

B4) Compliance

B5) Cost and Price Information

B6) Compliance with Evaluation Criteria

Step 1 – Eligibility

Submit Executive Summary by 12:00pm ET, June 4, 2019

- 5 Page Summary Limit
- ITAR & U.S. Commercial Provider certifications
- Prohibited countries representation
- Describe overall capacity to meet RSGS program requirements

Government will notify submitters whether qualified to propose

Those qualified will move to Step 2 . . .

Step 2 – Proposal Submission

Eligible proposal submitters will receive supplemental package and proposal submission instructions/due date

- 200 page limit
- Includes Proposal Summary
- Must have “team” defined and bus builder identified

Copy of OT template / terms included in supplemental package – submit updated OT with proposal as Appendix 1.

Appendix 2 – Supplemental Business Data

Submit full proposal by 5:00pm ET, July 23, 2019

Step 2 (cont'd) – Proposal Evaluation & Selection

Proposals will be evaluated in accordance with these evaluation criteria:

- Factor 1 – Technical Capabilities
- Factor 2 – Business and Management Plan
- Factor 3 – Consideration for Government Furnished Equipment and Services

DARPA intends to select a single partnership proposal for OT award

Step 3 – OT Negotiations and Award

OTs provide flexibility in the structure of the agreement. For example in the areas of:

- Intellectual Property
- Dispute Resolution
- Miscellaneous TBD issues

DARPA OT Template is merely a starting point. However, the following responsibilities are non–tradeable:

- Partner liability for on-orbit operation of the RSV
- Maintenance of appropriate personnel security

www.darpa.mil

Evaluation Criteria

Joseph Parrish
RSGS Program Manager

May 22, 2019

Proposal Evaluations

- All three factors are of equal importance.
- The three factors are all the evaluation criteria that the Government will use to evaluate a Proposer’s proposal.
- There are no unstated evaluation criteria.

Evaluation factors

- Factor 1 – Technical Capabilities
- Factor 2 – Business and Management Plan
- Factor 3 – Consideration for Government Furnished Equipment and Services

In the event of any conflict with the Program Solicitation (PS) document, the PS takes precedence.

Evaluation Factor 1 – Technical Capabilities

Providing a GEO-capable spacecraft bus:

- Extent to which the proposed bus has heritage in GEO operations, along with its ability to execute the RSGS mission operations over a multi-year operational lifetime.

Integrating the RSGS payload with the spacecraft bus:

- Extent to which the bus can accommodate the RSGS payload via extant capabilities and/or adaptations to the existing bus design; ease of integrating the RSGS payload to the bus to provide a complete RSV.

Integrating the combined spacecraft bus and RSGS payload with the launch vehicle:

- Extent to which the RSV can be integrated into the proposed launch vehicle.

In the event of any conflict with the Program Solicitation (PS) document, the PS takes precedence.

Evaluation Factor 1 – Technical Capabilities

Providing a launch vehicle:

- Extent to which the Partner-provided U.S.-manufactured launch vehicle is capable of delivering the fueled RSV to GEO orbit, either via GTO or direct to GEO.

Conducting GEO mission operations:

- Ability to conduct servicing operations in GEO, including experience with rendezvous and proximity operations, autonomous grappling operations, coupled stack operations, and robotic manipulator operations, over a multi-year operational lifetime.

Providing ground control station(s) and communications infrastructure:

- Extent to which ground facilities and communication infrastructure can integrate the GFE IRW and provide command and control of the RSV in operation throughout the GEO belt, at the required level of security, over a multi-year operational lifetime.

In the event of any conflict with the Program Solicitation (PS) document, the PS takes precedence.

Evaluation Factor 2 - Business and Management Plan

Viability of the public/private partnership:

- Financial capability and corporate commitment to fulfill the Partner’s responsibility in a public-private partnership, including the provision of a GEO-capable spacecraft bus, payload integration, launch vehicle integration, launch vehicle, GEO mission operations, and ground control station/communications infrastructure.

Providing an integrated and complete solution:

- The extent to which the Partner is capable of providing all equipment, personnel, resources, and facilities, without additional Government Furnished Property, Government Furnished Information, or Government Furnished Equipment, beyond those items discussed in this solicitation..

Efficacy of the business case:

- Extent to which a commercial business case exists for revenue-generating servicing operations to be performed upon multiple Government and commercial clients over a multi-year operational lifetime.

In the event of any conflict with the Program Solicitation (PS) document, the PS takes precedence.

Evaluation Factor 3 – Consideration for Government Furnished Equipment and Services

Extent of consideration offered to the Government related to:

- Reduced-price servicing of Government spacecraft
- Hosting of Government payloads/experiments
- Operational data and lessons-learned during the RSGS on-orbit operational lifetime
- Other types of consideration offered by the Proposer

In the event of any conflict with the Program Solicitation (PS) document, the PS takes precedence.

Questions should be addressed to:

DARPA-PS-19-01@darpa.mil

www.darpa.mil

RSGS Payload Overview

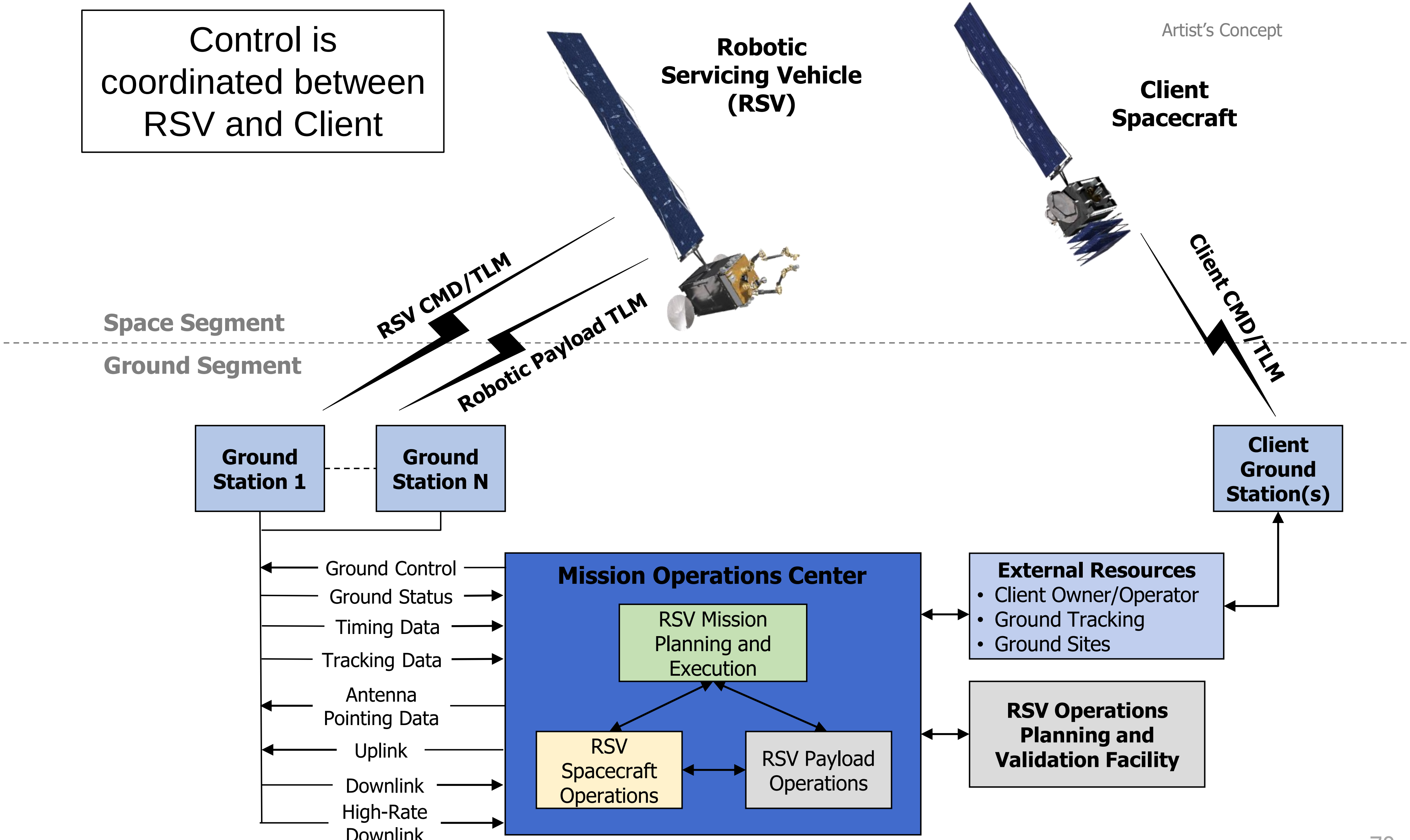
U.S. NAVAL RESEARCH LABORATORY

DARPA

U.S. Naval Research Laboratory
May 2019

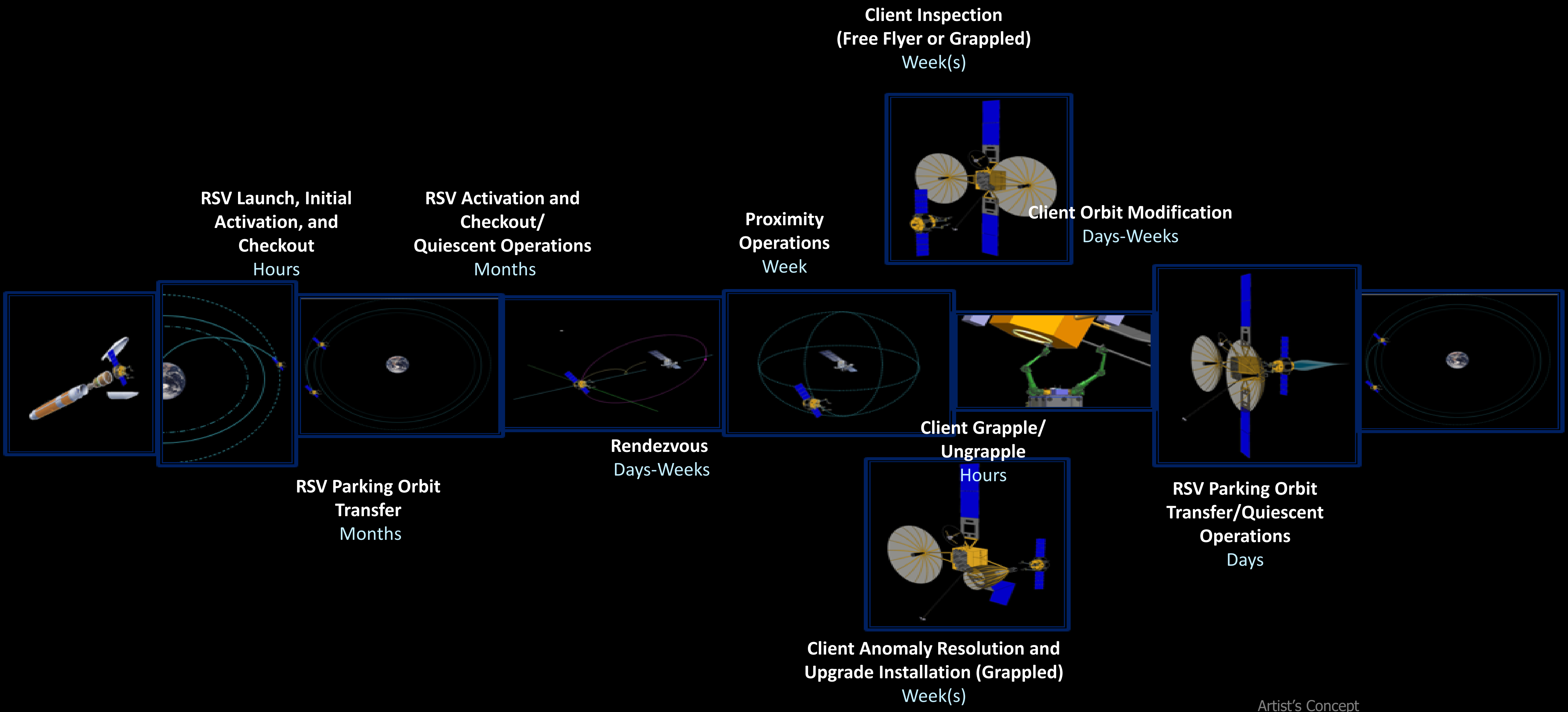
RSGS Mission Introduction

RSGS Architecture Block Diagram



DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

RSGS Concept of Operations



Artist's Concept

Payload Design Summary

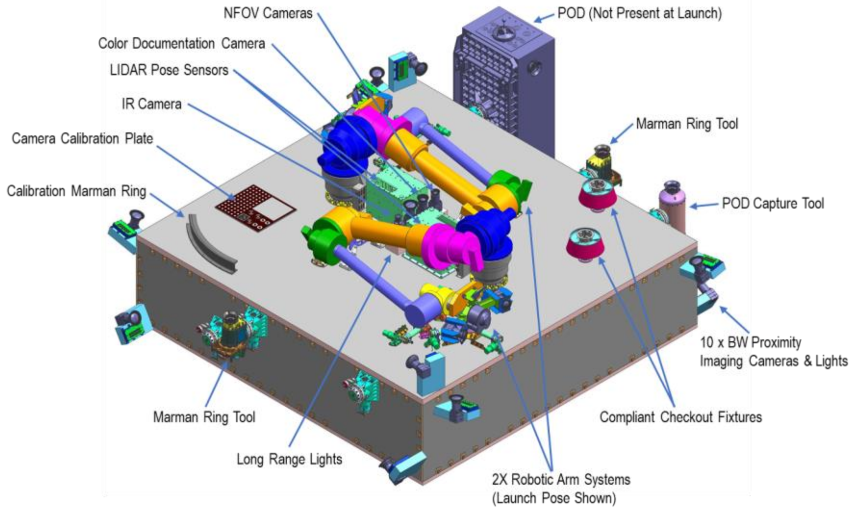
- DoD Class B reliability: Single fault tolerant to criticality 1 (mission ending) failures
  - Block redundant Robotic Arm Systems
    - Based on the assumption that 1 RAS is adequate to perform the full mission
  - Block redundant avionics
  - Block redundant orbit modification mission tools (first grapple tools)
  - Functionally redundant RPO
  - Robotic arm design allows for graceful degradation to arm faults
- Design practices, component selection, and design tolerance against single faults supports eight-year mission life
- 100 krad/Level 2 parts per EEE-INST-002; GEO Environment
- Protoqualification verification test program

Long-life payload leveraging DARPA investments will enable commercial missions for several years after government demonstration

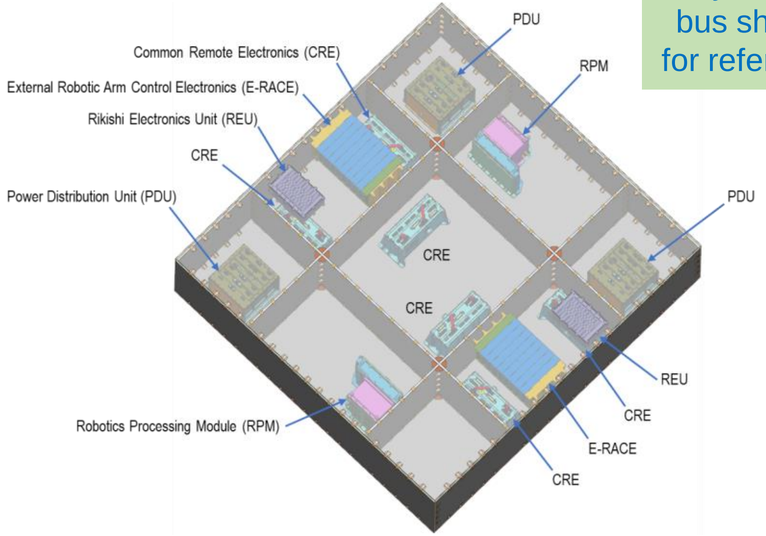
Payload Components

- 2 Robotic Arm Systems, each with:
  - 1 FREND Arm
  - 1 Rikishi Electronics Unit (REU)
  - 1 External Robotic Arm Electronics (E-RACE)
  - 1 End of Arm (EoA):
    - 2 Cameras
    - 3 Lights
    - 1 Tool Changer
    - 1 End of Arm Control Board (EACB)
- Flight Software (FSW)
  - Includes Payload Mission Manager (PMM)
- Algorithms
  - Marman Ring Detector (MRD)
  - POD Fiducial Detector (PFD)
  - Visual Servo (VS)
  - Position Control (PC)
  - Compliance Control (CC)
  - Torque Feed Forward (TFF)
  - RPO Bearing
- 7 SPDPs (Ports)
- Toolkit (3)
  - 2 Marman Ring Tools (MRT)
  - 1 POD Capture Tool (PCT)

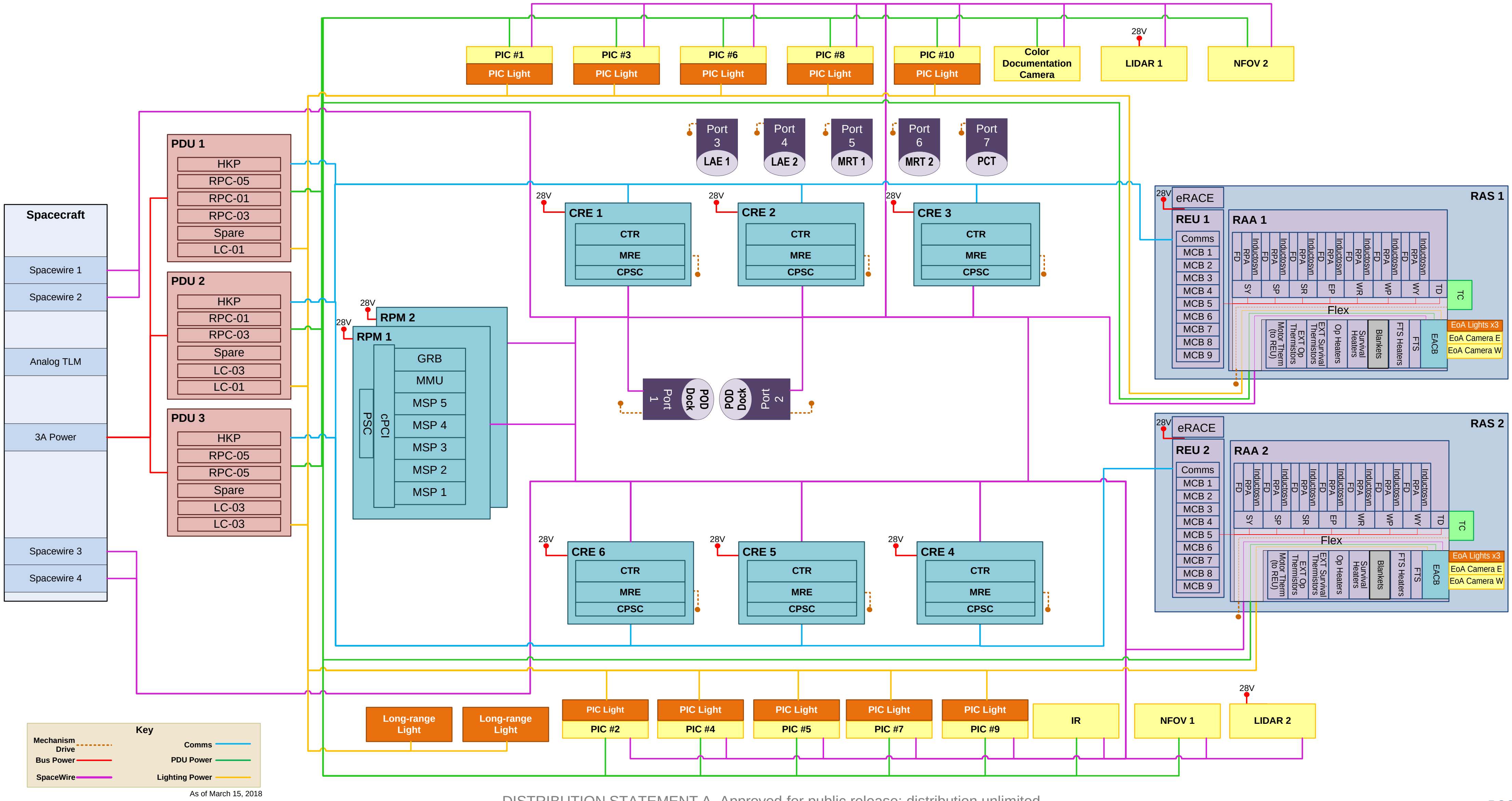
- Rendezvous and Proximity Operations Suite
  - 2 LIDAR Sensors
  - 2 NFOV Cameras
- Proximity Awareness System
  - 1 Color Documentation Camera (CDC)
  - 10 Proximity Imaging Cameras (PICs)
  - 1 Infrared (IR) Camera
- Deck-mounted Lights
  - 10 Proximity Imaging Lights
  - 2 Long-range Lights
- Command, Telemetry, and Data Handling
  - 6 Common Remote Electronics (CRE)
  - 2 Robotics Processing Modules (RPM)
- 3 Power Distribution Units (PDU)
- Calibration Hardware



Notional layout on bus shown for reference

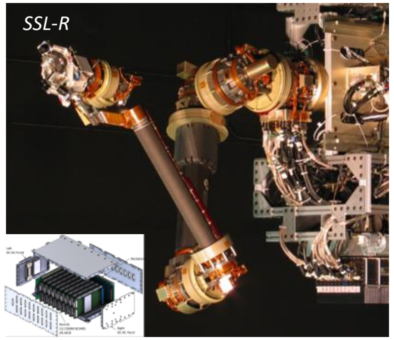


Payload Block Diagram



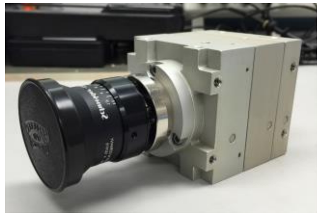
Payload Component Overview

Payload Components

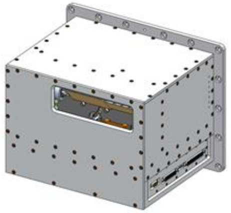


Robotic Arm Assembly
Post-CDR, Flight I&T in progress

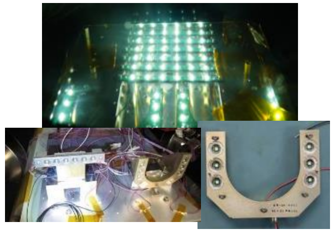
Oceaneering Space Systems
Tool Changer and Receptacle
Post-TRR, FM assembly and testing underway



Malin Space Systems
Panchromatic, Color, and IR Cameras
Post-MRR, EM testing underway, FM assembly in progress

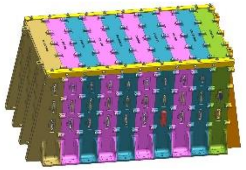


Neptec Design Group
LIDAR
Post-PDR, preliminary design in progress, long-lead parts procurement underway

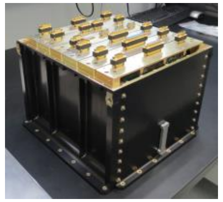


Payload Lighting
Post-CDR, EM testing underway, FM assembly in progress

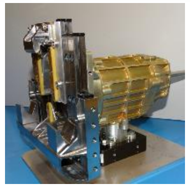
End of Arm Control Board
Post-CDR, EM testing in progress, FM fabrication underway

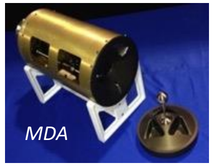


External Robotic Arm Control Electronics
Post-PDR, in FM design

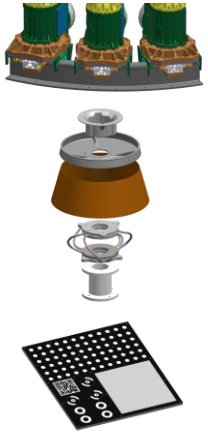


Power Distribution Unit
Post-CDR, EM testing in progress



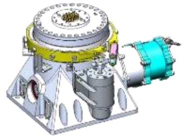


Toolkit
Marman Ring Tool – post-PDR, EM integration in progress
POD Capture Tool – pre-PDR

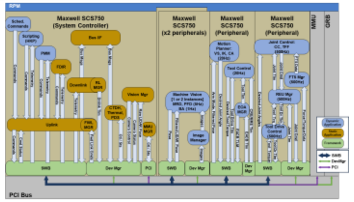


Calibration Suite
Post-PDR, EM design in progress

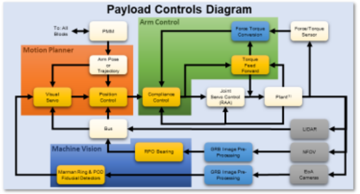
Robotics Processing Module and Common Remote Electronics
Post-CDR, EM assembly and testing underway



Sierra Nevada Corp
Structural, Power and Data Port
Post-PDR, in EM assembly



Payload Flight Software
Post-PDR, Build 3.4 pending release



Payload Algorithms
Post-CDR, verification in process

Payload hardware and software FM assembly, integration, and testing is underway

Robotic Arm System (RAS) Components

Robotic Arm System Overview

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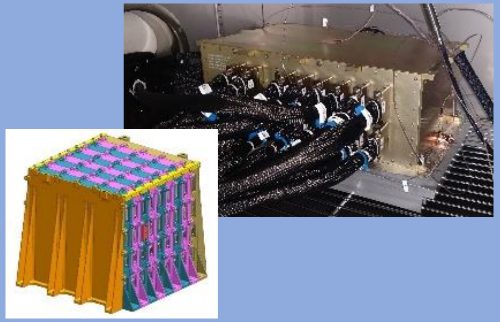
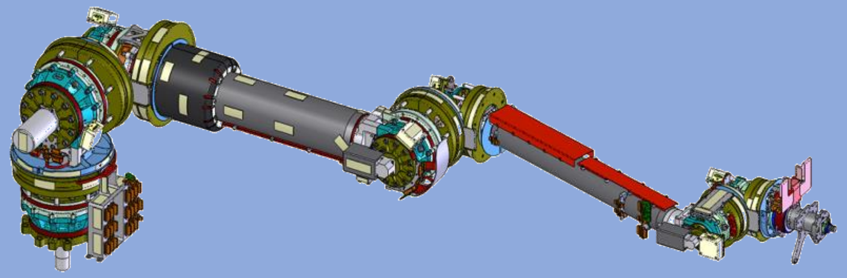
Robot Arm System (RAS)

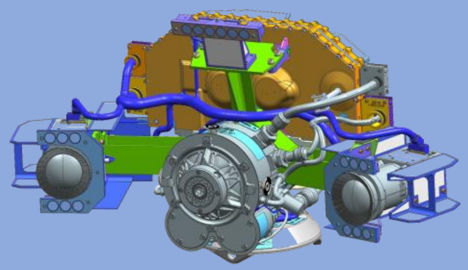
Robot Arm Electronics



Robot Arm (RA)

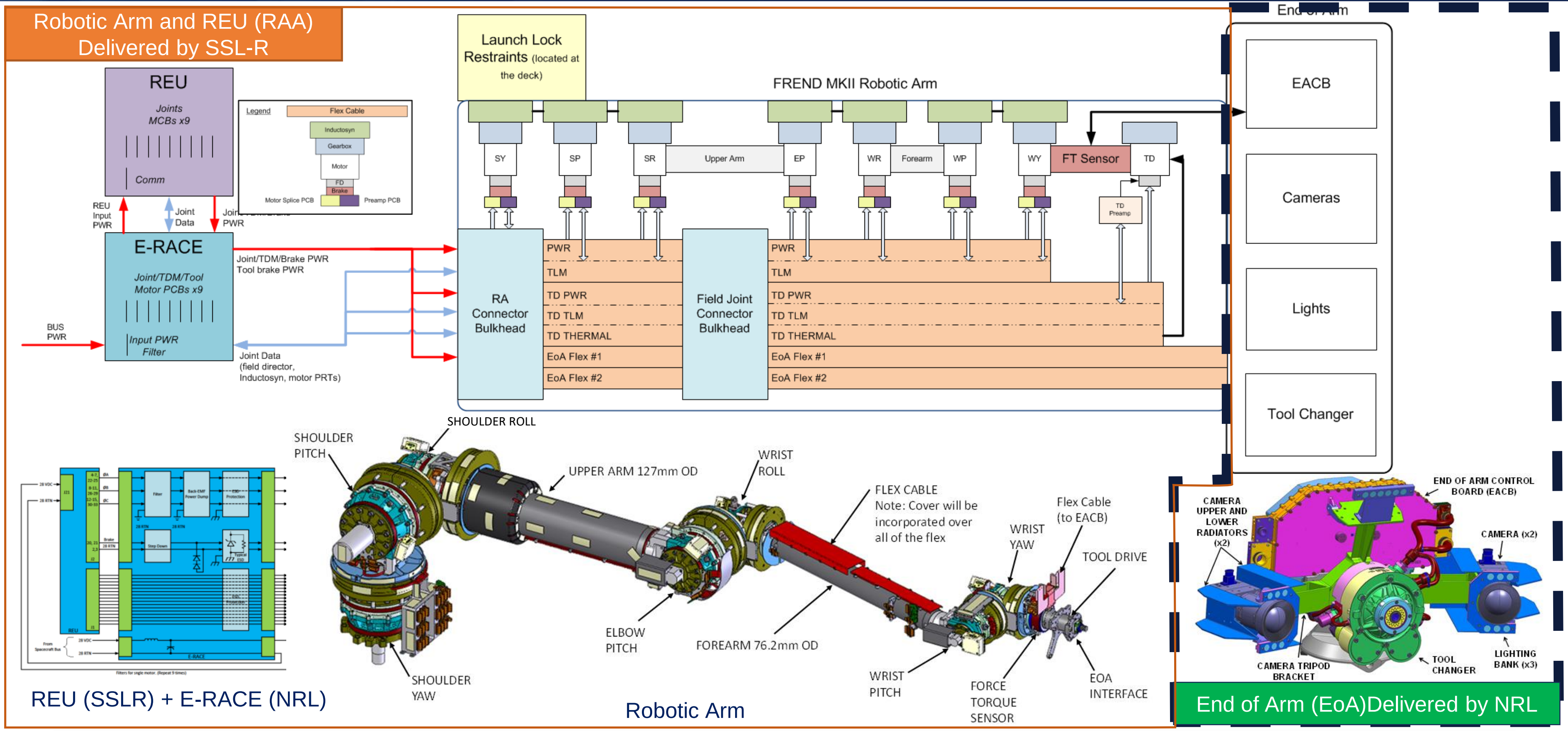


End of Arm (EoA)



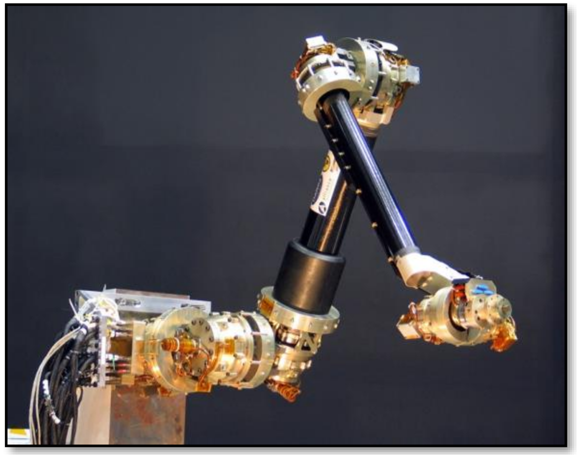
- The Robotic Arm System (RAS) is comprised of
  - The FREND Robotic Arm
  - Robot Arm Control Electronics
    - Rikishi Electronics Unit (REU)
    - External Robotic Arm Control Electronics (E-RACE)
  - End of Arm (EoA) components
    - Tool Changer, EoA Cameras, Lights, EACB, Structure, Harness

RAS Block Diagram

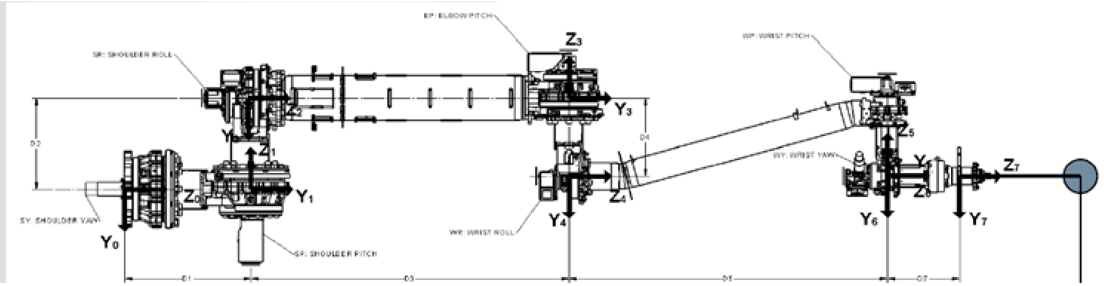


SSL-R delivers the RAA components (includes RA, REU, and launch locks)
Oceaneering Space Systems (OSS) delivers Tool Changer
Malin Space Science Systems delivers EoA Cameras
NRL delivers E-RACE, EACB, and the EoA (EoA lights, structure, harness, and thermal) then integrates and delivers the EoA
NRL integrates the RA with the EoA
NRL integrates the E-RACE and harness to complete RAS integration

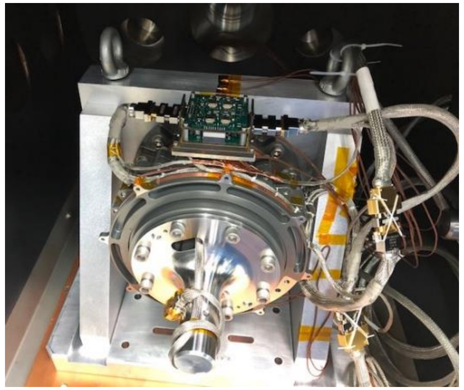
FREND MKII Robotic Arm



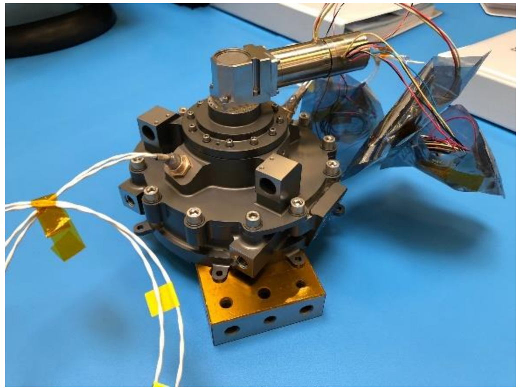
FREND Mark I, EDU



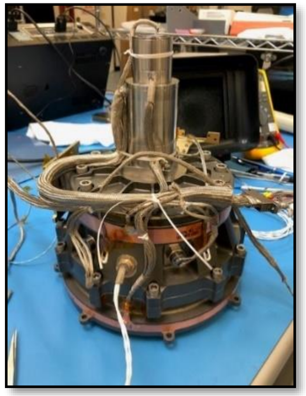
FREND Mark II Layout



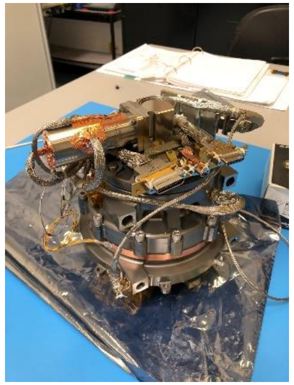
FM SY Actuator



FM WR Actuator



FM SP Actuator

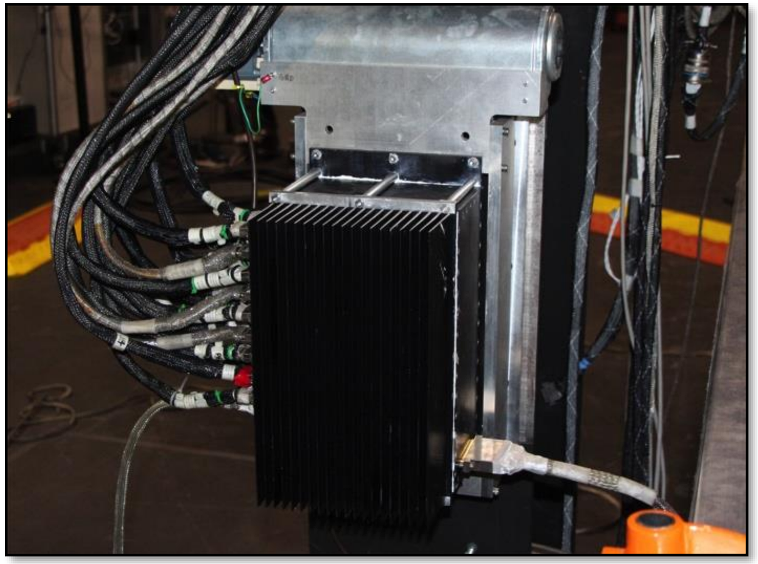


FM SR Actuator

- **Current Status:**
  - FM actuator assembly in progress
  - Arm #1 Delivery: Q3 2019
  - Arm #2 Delivery: Q4 2019

Rikishi Electronics Unit (REU)

- **Moog Broadreach (MBR), Phoenix, AZ delivers REU to SSLR, Pasadena**
- Robot Arm Control Electronics with:
  - 9 Motor Control Boards: 7 Joints, 2 Tool Drive
    - (SY, SP, SR, EP, WY, WP, WR, TD1, TD2)
  - 1 COMM Card
  - 1 Mother Board
- Mark I Rikishi EDU has been operating successfully since 2007
- Mark II FM REU upgrades include:
  - Primary/Redundant Comm interface
  - Individual power feeds per MCB
  - Updated Joint Control and FDIR logic



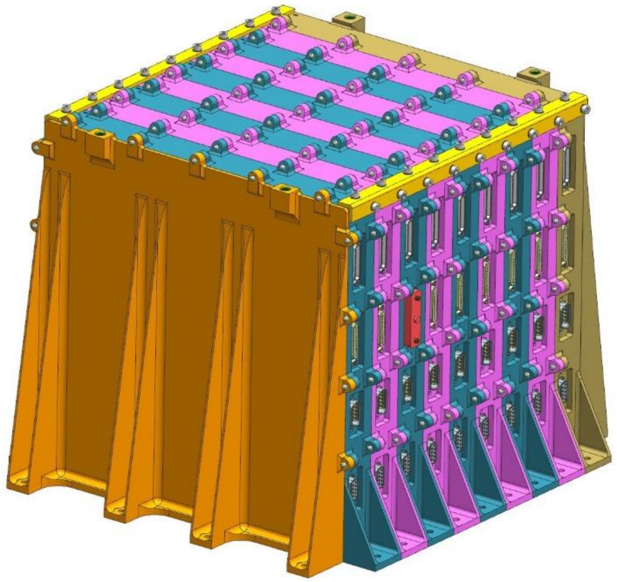
EDU MKI REU at NRL

FM MKII REU in Thermal Chamber

- **Current Status:**
  - Two EDU REUs currently in use at SSL-R supporting FM Arm test
  - FM REUs in test
  - FM REU #1 delivery: Q3 2019
  - FM REU #2 delivery: Q4 2019

External Robotic Arm Control Electronics (E-RACE)

- **NRL internal development and build**
- Purpose
  - Power filtering and extended arm operations
- Key Features
  - Match output impedance of REU to impedance of RA
  - Protect the REU and spacecraft power system from the back EMF of the motors
  - Provide a brake voltage step down voltage automatically after energization of the brake circuit
    - Joints and Tools
  - Provides ESD protection

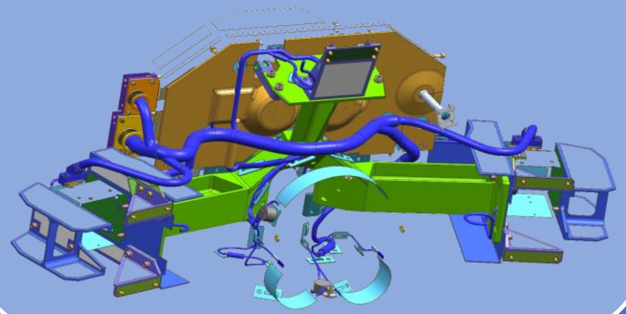


- **Current Status:**
  - Brassboard assembly in process, delivery in Q3 2019
  - EM and FM parts procurements underway
  - FM delivery: Q2 2020

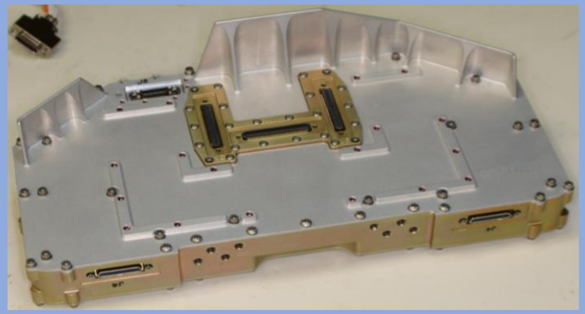
End of Arm Overview

End of Arm

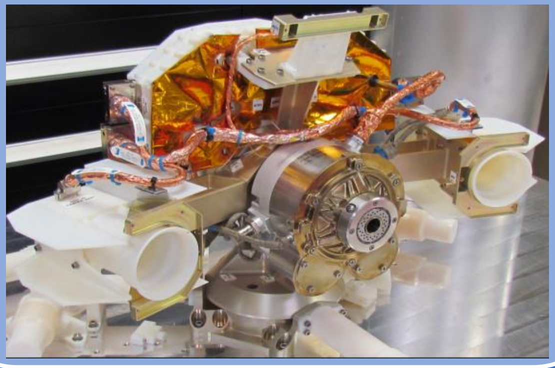
Structure/ Harness



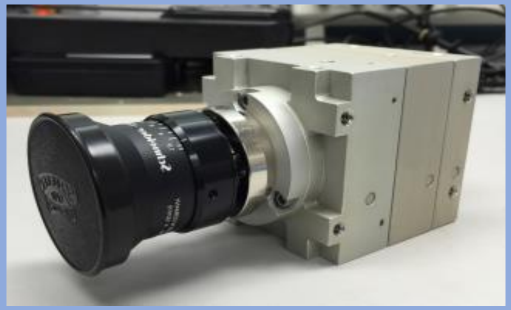
EoA Control Board



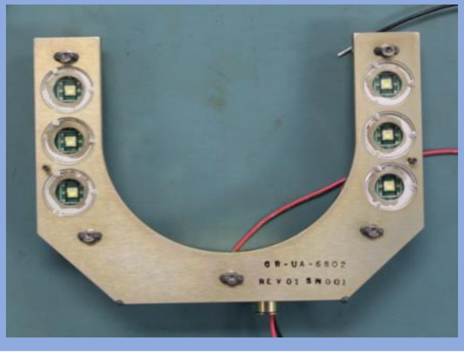
EoA Prototype



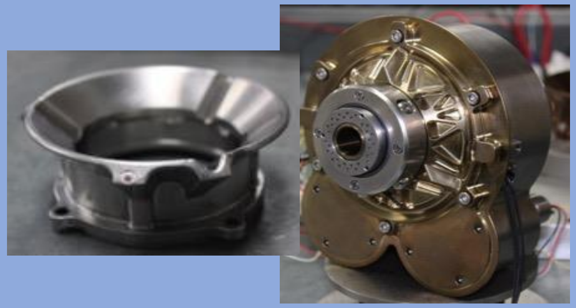
EoA Cameras



EoA Lights

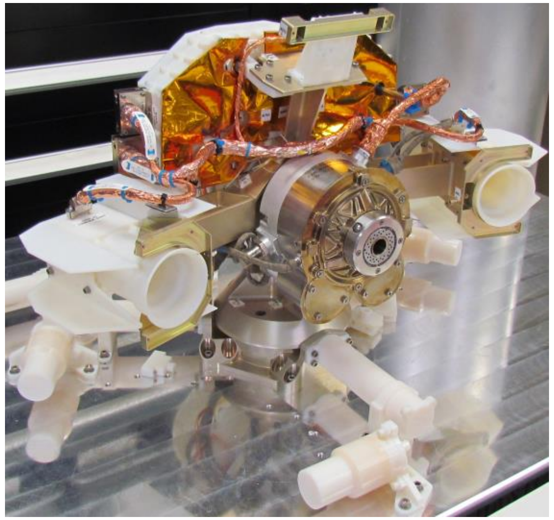


Tool Changer

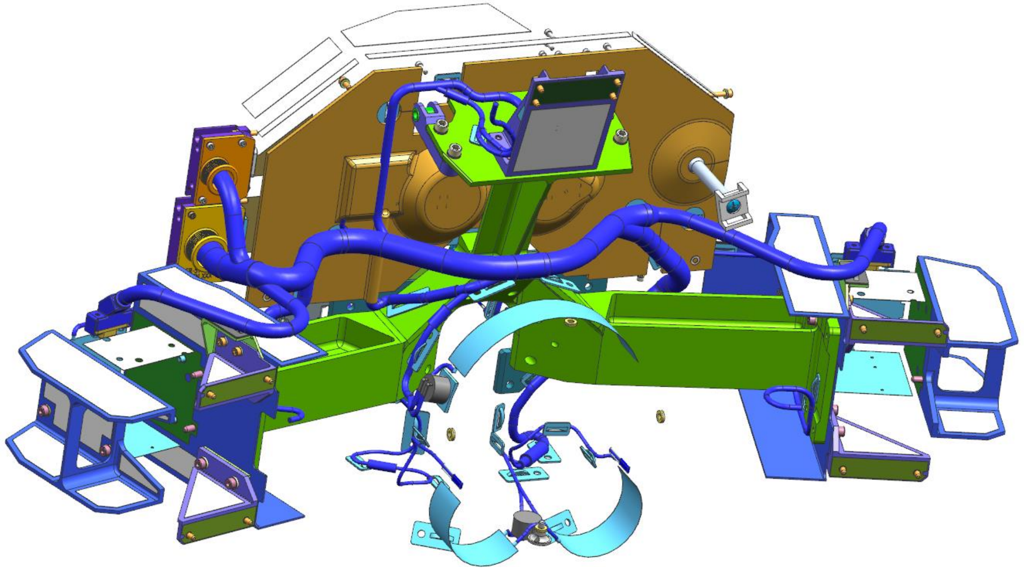


EoA Structure / Harness

- **NRL internal development and build**
- Components
  - Camera bracket
  - EACB lower bracket
  - EACB upper bracket
  - Lights brackets
  - Harness
  - Thermal hardware: radiators, PRTs, heaters, thermostats



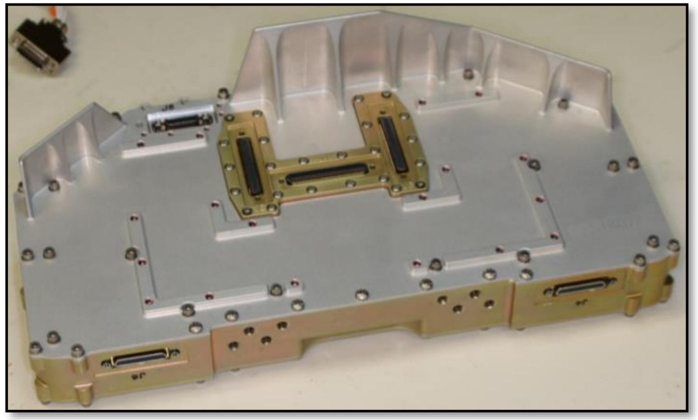
End of Arm Rapid Prototyped Structure



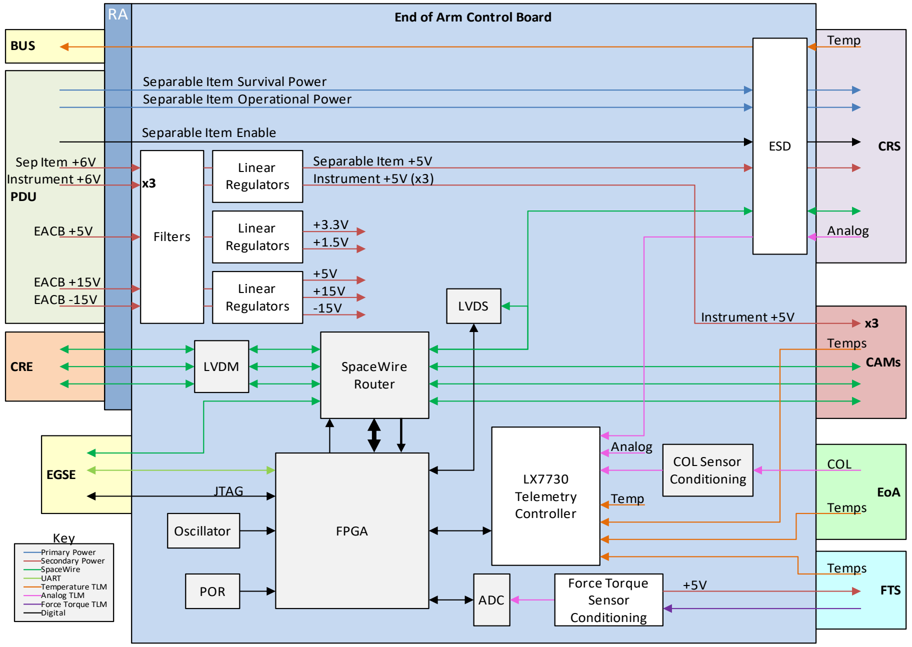
- **Current Status:**
  - FM Brackets complete
  - FM harness assembly underway
  - FM thermal hardware on order

EoA Control Board (EACB)

- **NRL internal development and build**
- Purpose
  - Functions as interface between most of End of Arm (EoA) components & payload
  - Power to and SpaceWire communications with two EoA cameras
  - Power and command to; and telemetry from the mated tools via the tool changer Common Receptacle Subassembly (CRS)
  - Power to and telemetry from the Force Torque Sensor (FTS)
  - Telemetry from the tool changer Confirmation-of-Lock (COL) sensor
- EDU successfully tested with RA Flex Harness and operated since April 2017



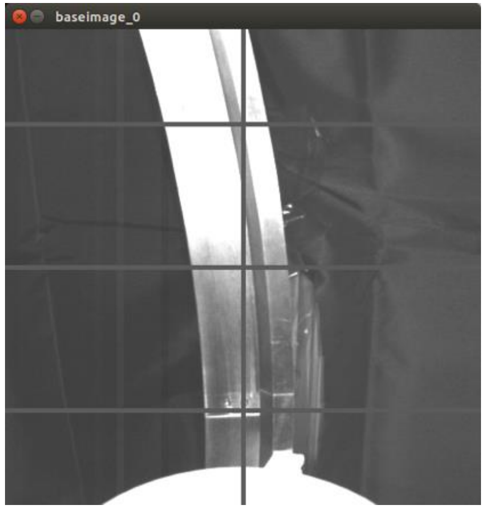
EACB EM Cover



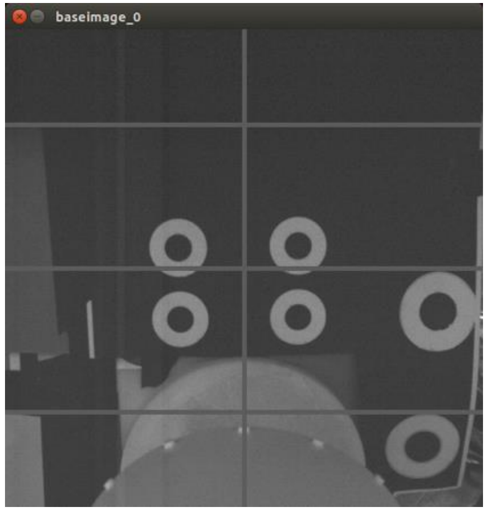
- **Current Status:**
  - EM EACB environmental testing is underway
  - FM EACB #1 & #2 assembly in process
  - FM EACB delivery: Q1 2020

EoA Cameras

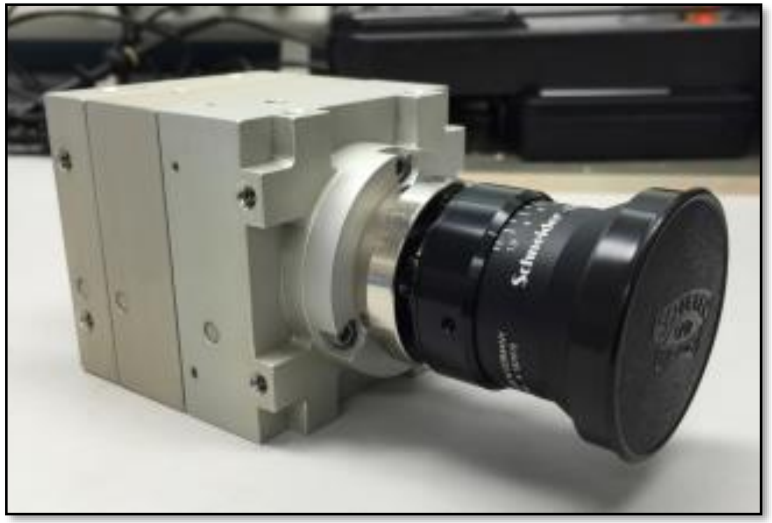
- **Malin Space Science Systems (MSSS), San Diego, CA**
  - Extensive experience with spaceflight cameras
- SpaceWire interface for communications and image output
- Imagery is used as primary input into machine vision algorithms
- Imagery to be recorded for close-proximity, close proximity inspection missions and teleoperations
- Camera placement carefully chosen to work with tools and RSO features



Gridlines overlay with Marman Ring



Gridlines overlay with POD Fiducial

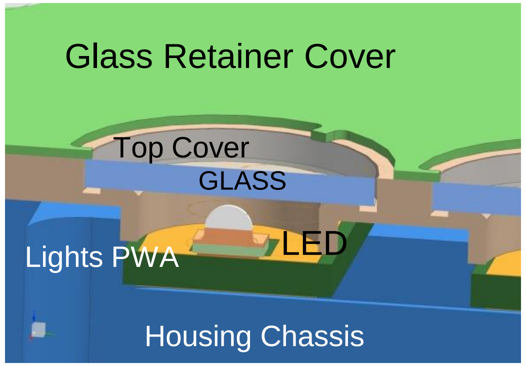


EDU EoA Camera

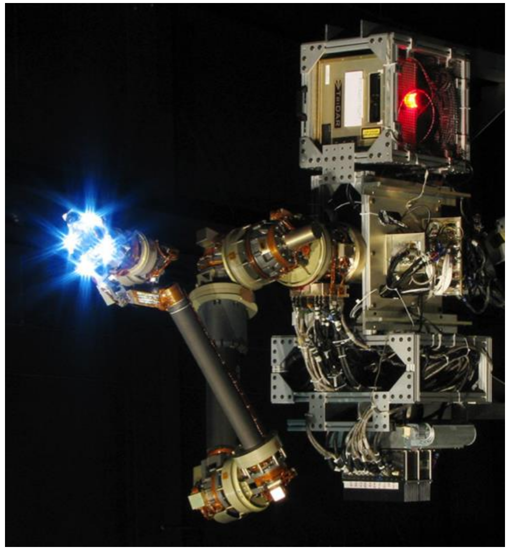
- **Current Status:**
  - EDU cameras received
  - EM camera delivered April 2019
  - FM cameras in assembly
  - FM delivery: Q3 2019

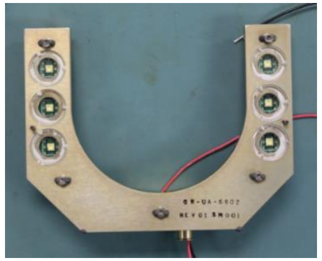
EoA Lights

- **NRL internal development and build**
  - In conjunction with NRL code 7200 remote sensing group
- East/West lights are designed to be collocated with each camera
- North lights are a light-bar to provide fill illumination
- LEDs completed successful radiation testing in April 2018

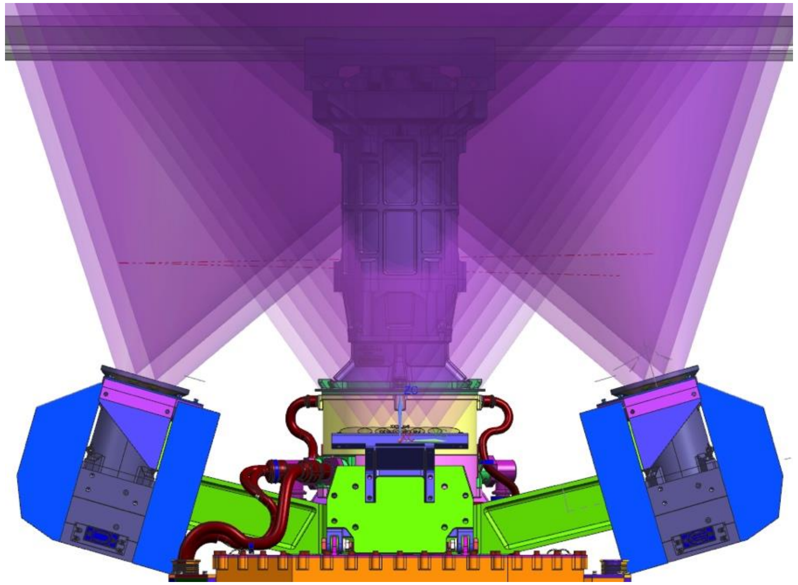


Single LED Assembly Detail





EAST/WEST EoA Light

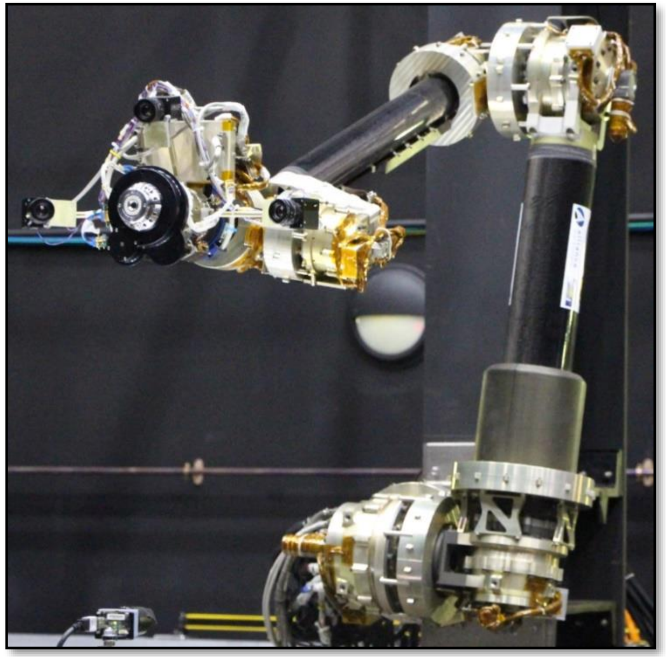


All EoA Lights Illumination Pattern

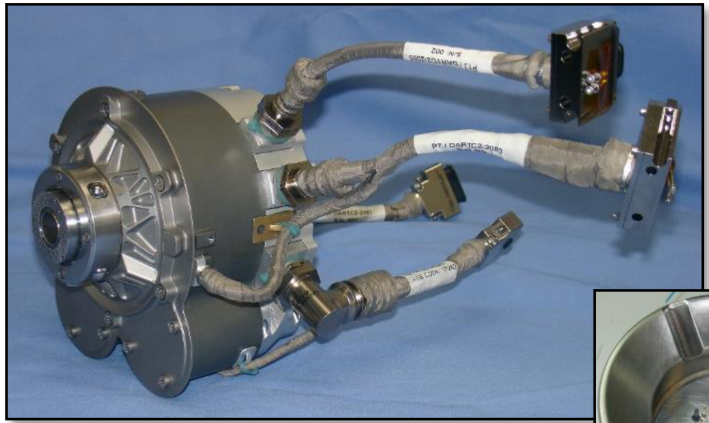
- **Current Status:**
  - EM lights in test
  - FM delivery: Q4 2019

Tool Changer and Receptacle (TCR)

- **Oceaneering Space Systems (OSS) Houston, TX**
- Provides the common structural, torque, and electrical mechanical interface for on-orbit tool attachment
- Oceaneering prototype has been operating successfully at NRL since 2014
- Common Receptacle Subassembly to be integrated onto all tools, delivered by OSS



Prototype Tool Changer on EDU RA



FM Tool Changer #1

FM CRS

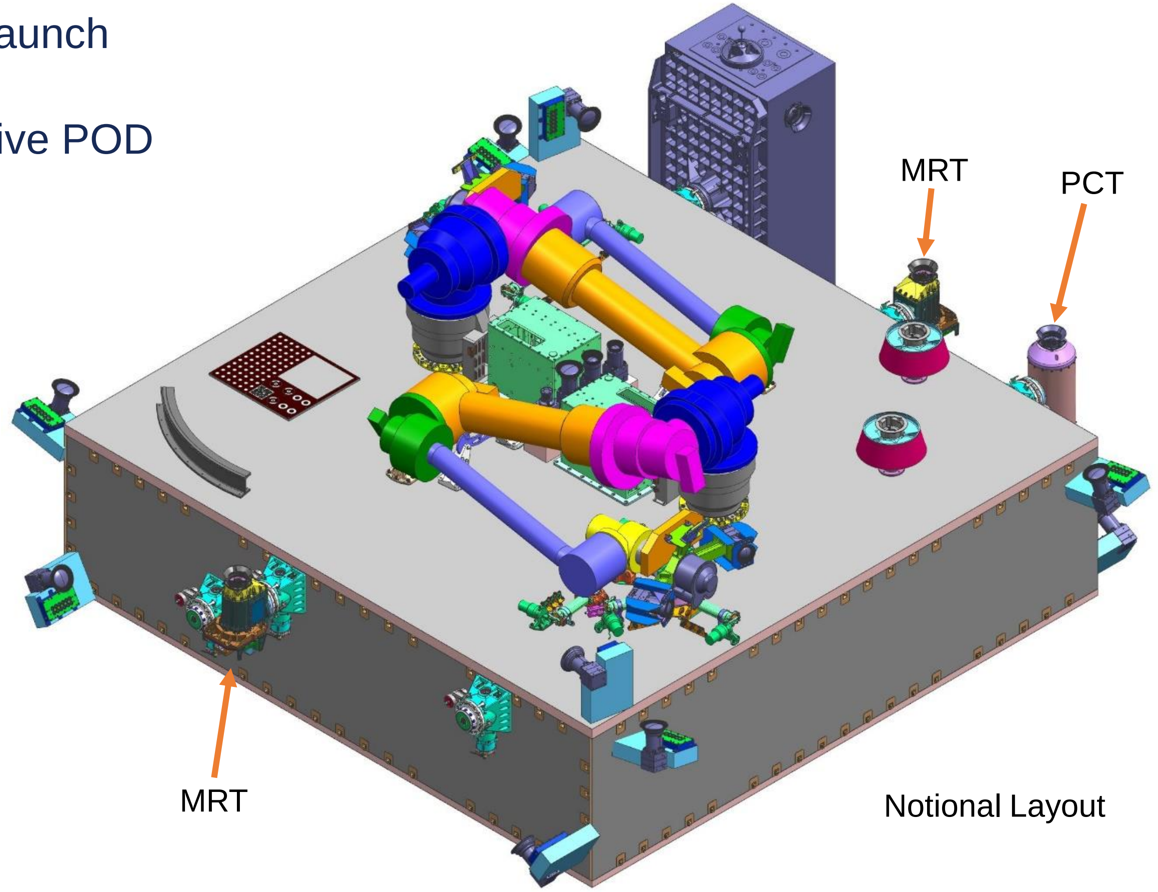
- **Current Status:**
  - EM delivered Q1 2019
  - FM #1 assembled and starting performance testing
  - FM #2 assembly is underway
  - FM delivery: Q3 2019

Toolkit Components

Toolkit Overview

- The Payload Toolkit consists of:
  - 2x Marman Ring Tool (MRT): Grapples via the marman ring launch vehicle interface common on GEO vehicles
  - 1x POD Capture Tool (PCT): Grapples POD via the cooperative POD Grapple Fixture

- 7x Structural, Power and Data Ports (SPDPs)
  - 3x Stow tools for launch and when not in use
  - 4x for POD & OAC staging



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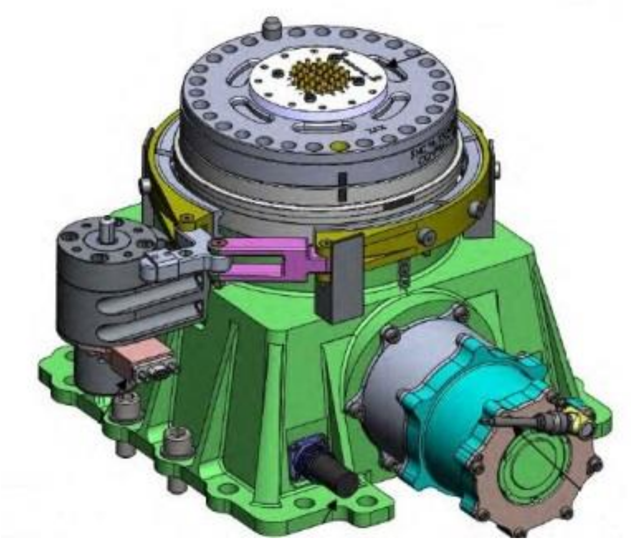
Structural, Power and Data Port (SPDP)

- **Sierra Nevada Corporation, Durham NC**
- The Active Unit is permanently attached to the spacecraft payload deck.
- The Passive Unit is permanently attached to a separable item (Tool/POD/OAC).
- The Port serves two primary functions:
  - Launch restraint and release of tools
  - Storage of Separable Items, Tools/PODs/OACs
    - Repeated on-orbit mate & de-mate
    - Electrical pass-through to separable items for on-orbit operations

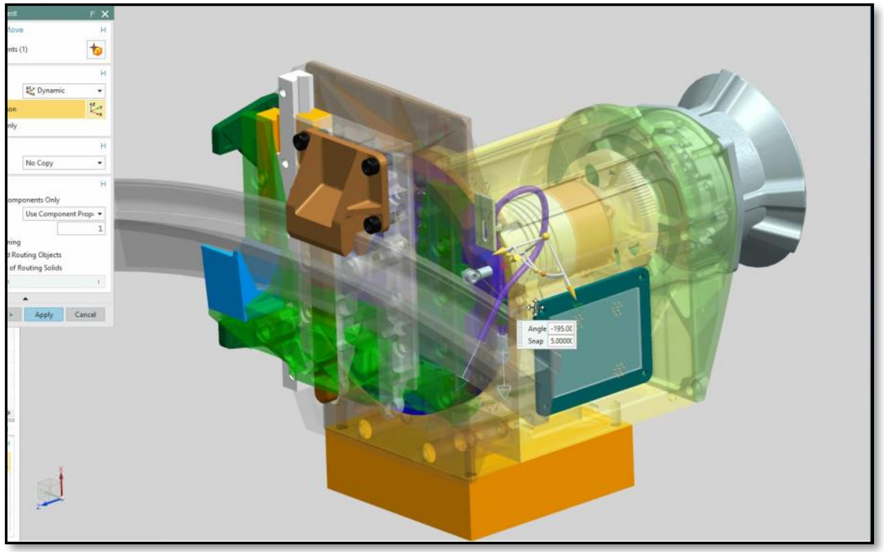


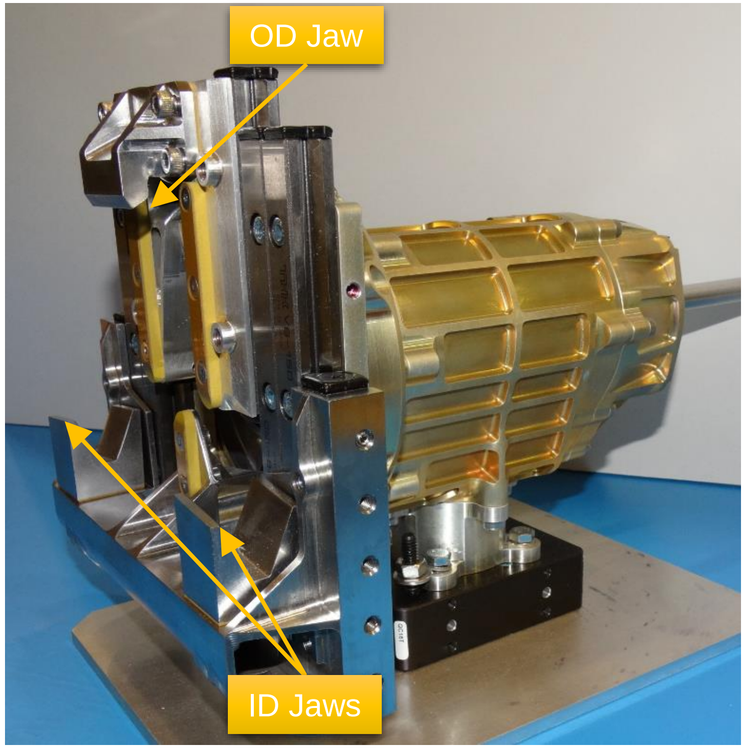
SPDP Active Unit

- **Current Status:**
  - EM fabrication is underway
  - EM delivery: Q4 2019
  - FM delivery: Q3 2020

Marman Ring Tool (MRT)

- **NRL internal development and build**
- Evolved design from FREND Demonstration
- Grapples 1194, 937, & 1666 Marman Rings
- Establishes structural link to RSO
- Includes resistive bleed path for first contact
- Prototype Testing in progress
  - Stiffness testing completed
- Closing FM design trades



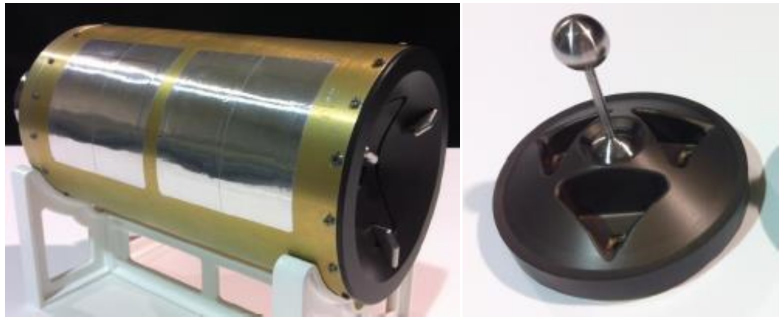


Prototype Marman Ring Tool

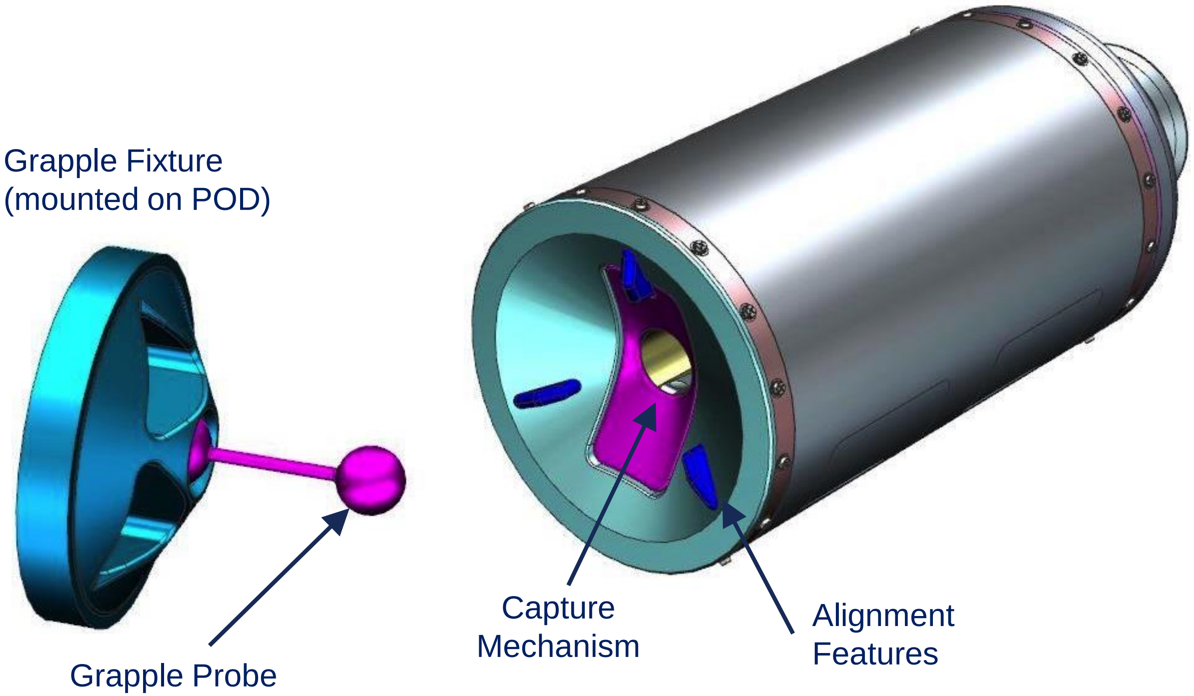
- **Current Status:**
  - EM assembly is underway
  - EM delivery: Q3 2019
  - FM delivery: Q3 2020

POD Capture Tool (PCT)

- **MDA Brampton, Canada**
- Evolved version of Orbital Express End Effector
  - Incorporates Telemetry Lessons Learned
  - Updates interfaces to be compatible with RSGS
- Grapples POD via PCT Grapple Fixture



POD Capture Tool Prototype



- **Current Status:**
  - EM delivery: Q4 2019
  - FM delivery: Q4 2020

Avionics and Sensors Hardware Overview

Robotics Processing Module (RPM)

- **RPM is a mix of procured and NRL in house developed components**
- Functions
  - SpW Router
    - Distributes SpW Time
    - Receives Force/Torque Sensor (FTS) and Joint Command Interface (JCI) TLM via SpWN
    - Receives payload SoH TLM
    - Receives all camera image streams
    - Transmits Mass-memory data to Wide-Band downlink
  - Image pre-processing (JPEG, Threshold, Edge, Moment)
  - Mass storage: 200GB EOL
  - Hosts FSW
    - Image processing, FTS/JCI TLM interpretation, arm commanding, arm collision avoidance
  - Redundant RPM kept in cold standby
- Key Elements
  - GRB Uses a reprogrammable FPGA (RTG4)
    - Not reprogrammable in orbit
  - 5X Maxwell SCS750 Single Board Computers (800 Mhz)
  - One SwRI Mass Memory Unit

EM RPM

- **Current Status:**
  - EM assembled and performance testing is underway
  - FM card assembly is underway
  - FM delivery: Q4 2019

Common Remote Electronics (CRE)

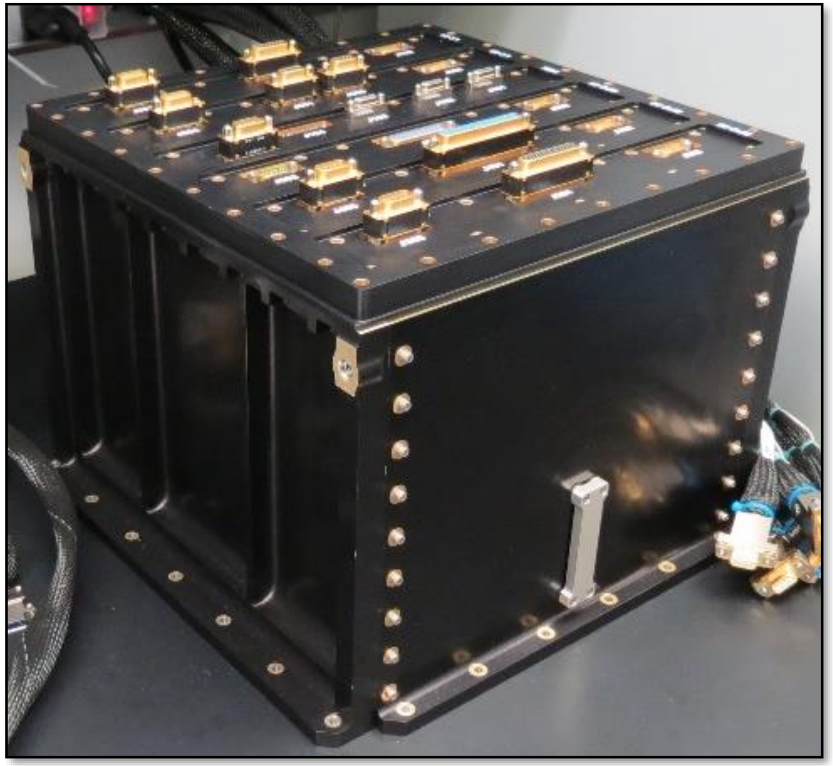
- **NRL internal development and build**
- Functions
  - SpW Router/Gateway
    - Primary Interface for lower rate digital data: PDU (LVDS) & REU (RS-422)
    - Distributes SpW Time
    - Supports SpW RMAP
  - Mechanism driver for Tool Changer and SPDP
  - Analog TLM Conversion
  - Provides ESD protection for signals read from components outside the SC structure
- Key Elements
  - Uses a reprogrammable FPGA (RTG4)
    - Not reprogrammable in orbit
  - Uses LX7730 Analog Telemetry processor (Reconfigurable on orbit)
  - Identity connector to load box unique configurations

EM CRE

- **Current Status:**
  - EM assembled and performance testing is underway
  - FM card assembly is underway
  - FM delivery: Q2 2020

Power Distribution Unit (PDU)

- **NRL internal development and build**
  - Housekeeping card (HSK)
  - Regulated Power Card (RPC)
  - Lighting Card (LC)
  - Mother board
- Each PDU has a different set of cards based on the loads it is servicing
- Functions
  - Provides regulated power to:
    - Narrow Field of View (NFOV) Cameras
    - Proximity Imaging Cameras (PICs) and PIC Lights
    - Infrared (IR) Camera and Color Documentation Camera (CDC)
    - Long Range (LR) Lights
    - Voltage compensated circuits for End of Arm Components
      - End of Arm Control Board (EACB)
      - End of Arm (EoA) Cameras and Lights
  - Provides command and telemetry interfaces to the Command, Telemetry, and Data Handling (CT&DH) system
  - Provides overcurrent protection
- Key Features
  - PDU Uses a reprogrammable FPGA (RT4G)
    - Not reprogrammable in orbit



EM PDU

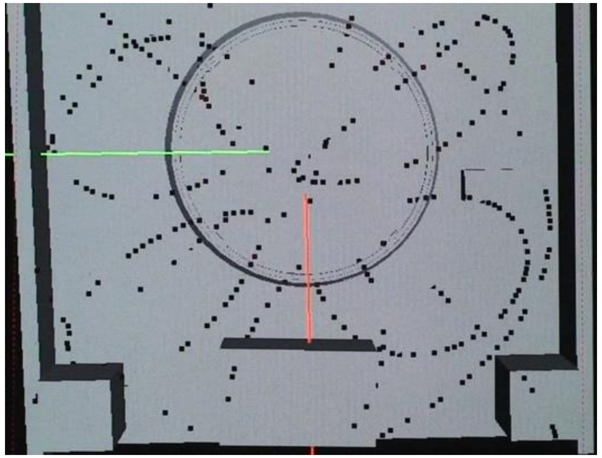
- **Current Status:**
  - EM assembled, performance testing is underway, environmental testing is pending
  - FM card assembly in underway
  - FM delivery: Q3 2020

Sensors and Lighting Hardware Overview

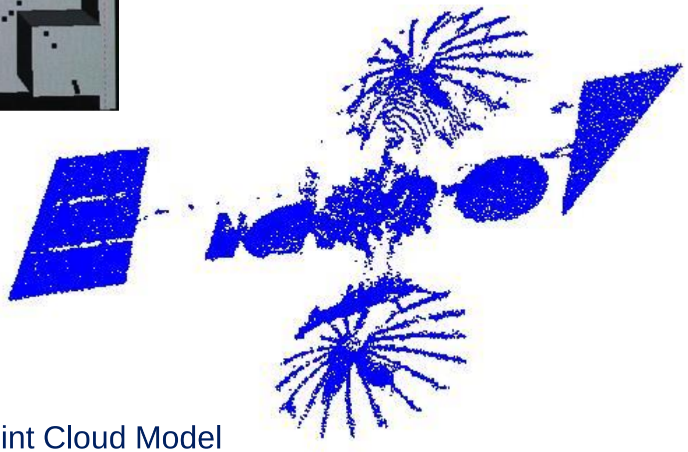
LIDAR Overview

- **NEPTEC Design Group Kanata, Canada**
  - Variants have Flown on Shuttle and Cygnus Mission
- Functions
  - 3D POSE range <1km
  - 6D POSE range <50 m
  - Generate Point Cloud to support building models of client Spacecraft
- Key Elements
  - Reprogrammable FPGA (RTG4)
  - Optics are based on heritage designs
  - Heritage FSW use for POSE calculation
- Risk Reduction
  - Neptec has performed significant mechanism life tests
  - Extensive modelling/Simulation capability

NEPTEC Tridar



POSE Scan



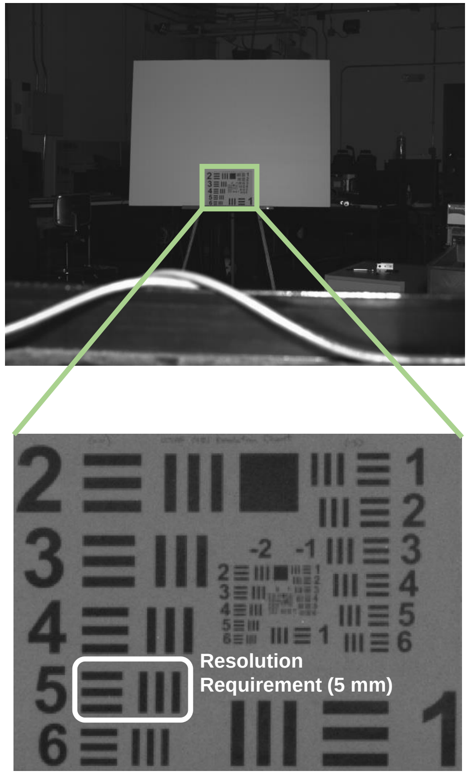
Point Cloud Model

- **Current Status:**
  - EDU delivery: Q4 2019
  - FM delivery: Q3 2020

NFOV Camera Overview

- **Malin Space Science Systems (MSSS), San Diego, CA**
  - Cameras flown on Interplanetary and selected for RESTORE mission
- Functions
  - Bearing POSE range >1km
  - Inspection of RSOs from distance and Close-in
- Key Elements
  - On-Semiconductor CMOS Imager
  - Optics are based on heritage designs
- Risk Reduction
  - EDU Units have been developed and tested
  - Performed testing with COTS version of flight imager
  - EM NFOV camera currently in test

NFOV COTS Camera Image On-Axis
40 msec at 5 m



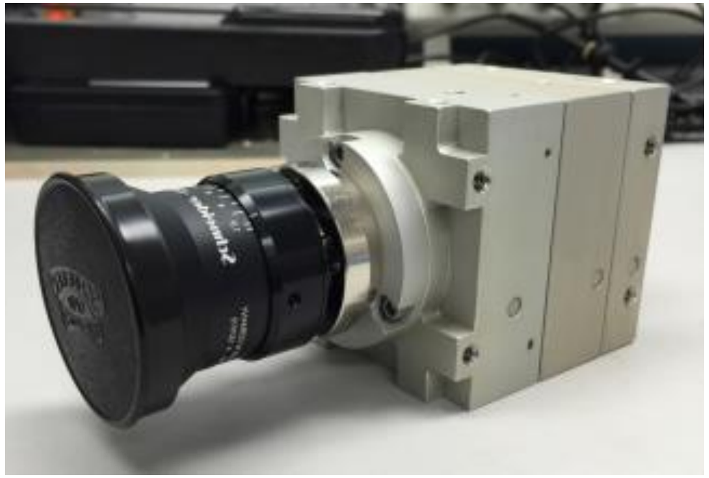
- **Current Status:**
  - EM NFOV delivered in April 2019
  - FM delivery: Q4 2019

U.S. NAVAL RESEARCH LABORATORY

PIC, CDC, IR Cameras

DARPA

- **Malin Space Science Systems (MSSS), San Diego, CA**
  - Cameras flown on Interplanetary and selected for RESTORE mission
- Functions
  - PICs: Witness Robotic Operations
  - CDC: Color inspections of RSOs
  - IR: Thermal inspections of RSOs
- Key Elements
  - Visible: On-Semiconductor CMOS Imager
  - IR: ULIS Microbolometer
  - Optics are based on heritage designs
- Risk Reduction
  - EDU Units have been developed and tested
  - Commercial Version of the Sensor have been used to support testing at NRL



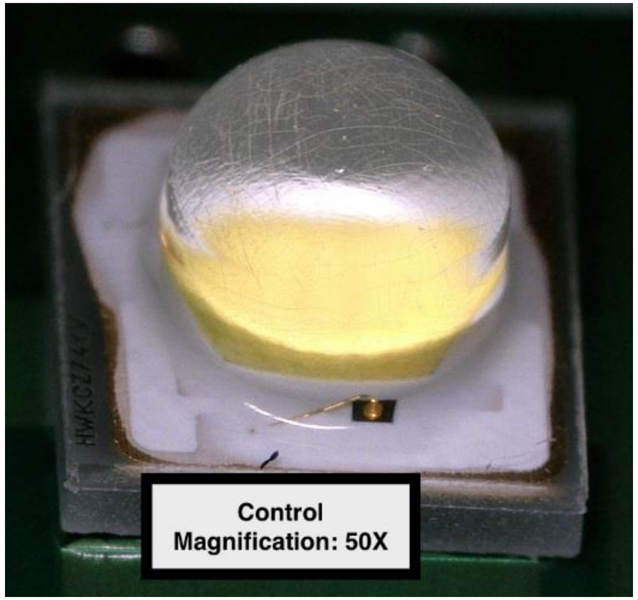
EDU PIC

IR Camera

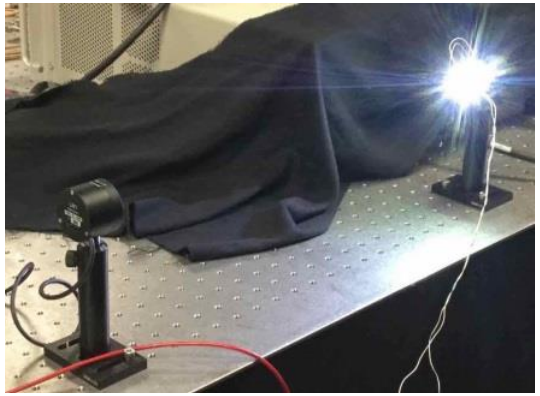
- **Current Status:**
  - EM IR & CDC Cameras delivered April 2019
  - EM PIC delivery: Q3 2019
  - FM camera delivery Q4: 2019

Deck Lights

- **NRL internal development and build**
- Functions
  - PIC Lights: Support PIC camera imaging of robotic operations
  - Long Range Lights: Support imaging of RSO from 5m
- Key Elements
  - OSRAM LEDs selected
  - Lights contain a current balancing circuit
  - 50 mils of glass added for radiation shielding
- Risk Reduction
  - Total Dose testing performed on LED at NRL
  - Displacement Dose Damage Testing performed at University of Washington
  - Lights are within their allocated losses



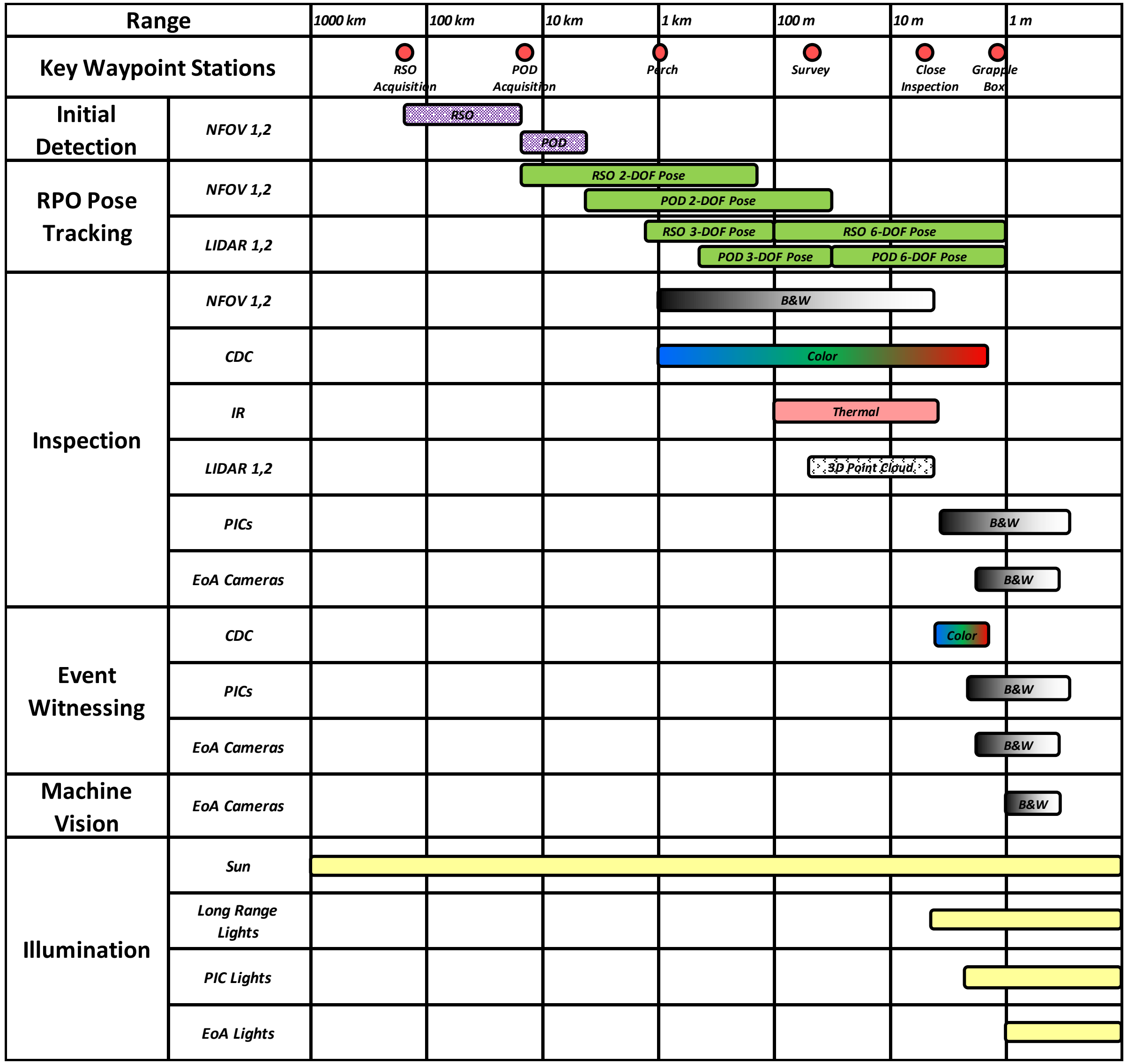
Newport 918D Detector looking at single LED



Radiation Test Board with 1 LED lit

- **Current Status:**
  - EM Deck Lights in environmental testing
  - FM delivery: Q4 2019

Sensor & Lighting Operating Range Summary



Controls & Algorithms Overview

Controls, Algorithms, & Sensors (CAS) Component Block Diagram

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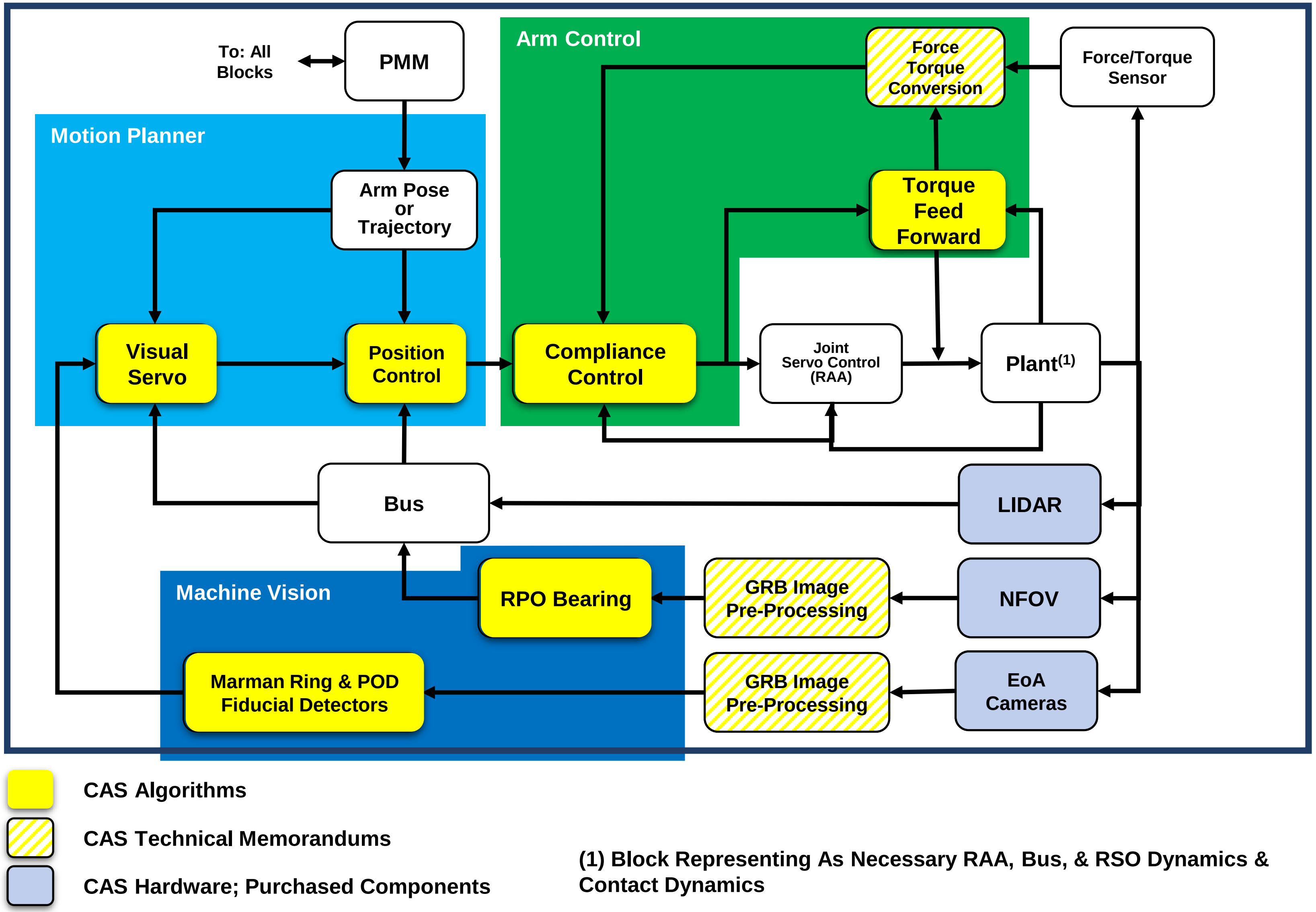
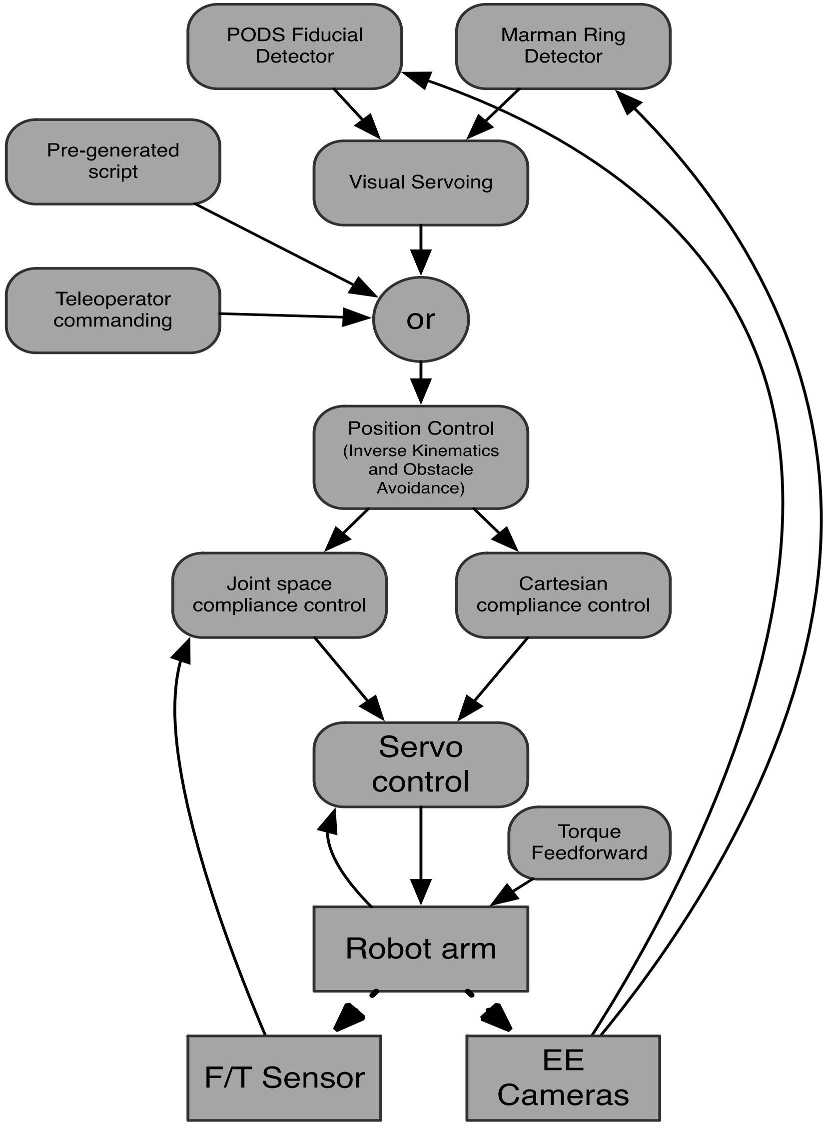


(1) Block Representing As Necessary RAA, Bus, & RSO Dynamics & Contact Dynamics

Algorithm Overview

- The RSGS algorithm stack–up is very similar to the stack–up that was used for the FREND demos (circa 2007–2008) and for all subsequent demos and development efforts
  - Inverse kinematics and collision avoidance algorithms (known here as “Position Control”) were rewritten from scratch for RSGS
- Status:
  - All algorithms are complete and algorithm level verification is underway
  - Implemented in FSW:
    - Compliance Control, Position Control, Marman Ring Detector, POD Fiducial Detector
  - FSW Implementation in process:
    - Visual Servo

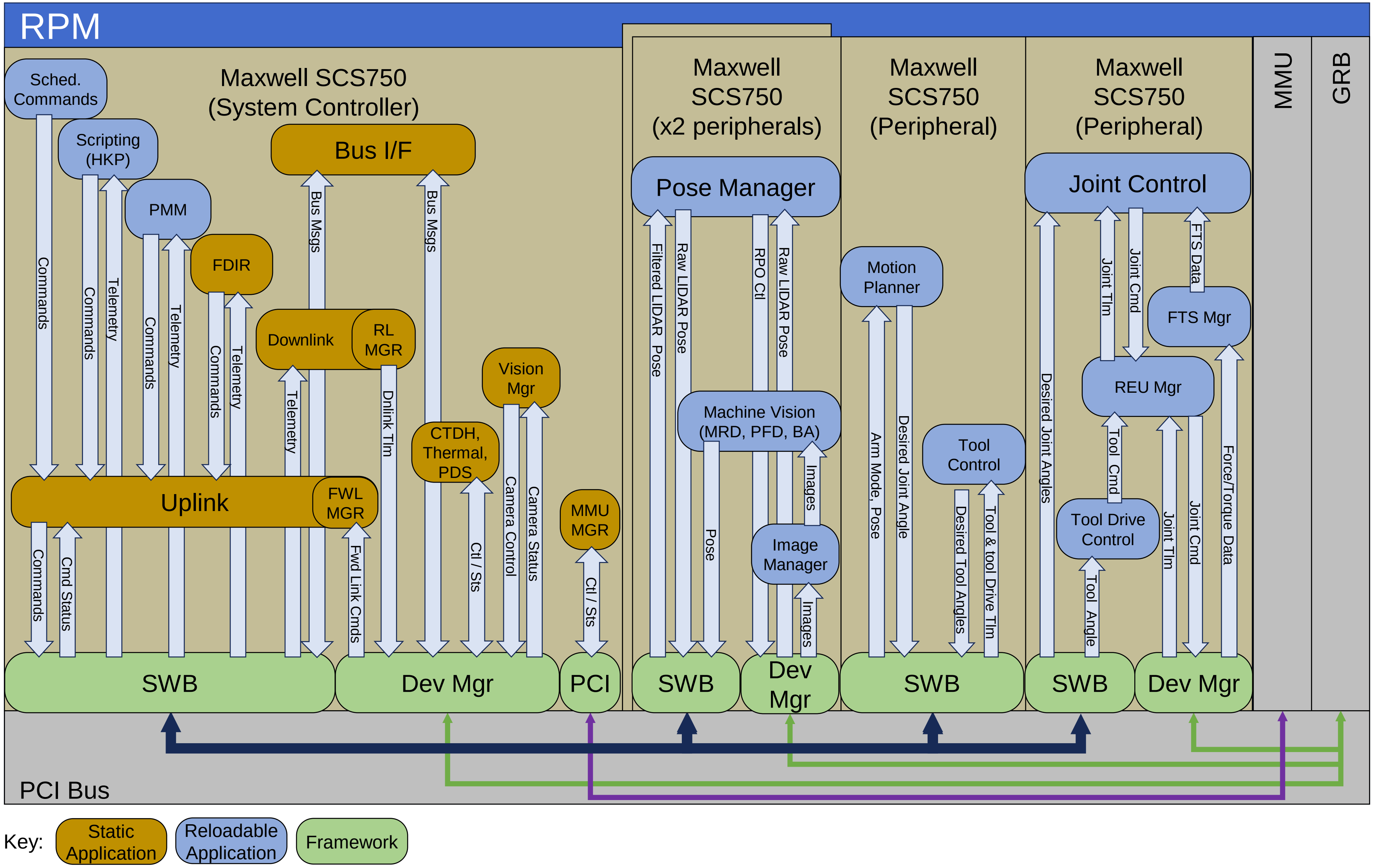


Flight Software (FSW) Overview

Payload FSW Description

- The RSGS Payload Flight Software (FSW) resides in the RPM
- The FSW provides control of the 2 robotic arms
- The FSW implements the various robotic control algorithms, including:
  - Machine Vision Detectors (Marman Ring Detector, POD Fiducial Detector)
  - Position Control
  - Visual Servoing
  - Compliance Control
  - Torque Feed Forward
  - RPO Bearing Estimation
- The FSW implements the payload mission management and FDIR
- The FSW provides a high-level scripting capability and time based commanding
- The FSW provides an interface to the spacecraft bus to accept commands and provide telemetry
- The FSW collects and reports payload state of health and diagnostic telemetry
- The FSW provides configuration, command and status collection of the CTDH and other payload hardware
- FSW executes on 5 Maxwell SCS750 processors in the RPM and utilizes WindRiver's VxWorks OS

Simplified FSW Architecture



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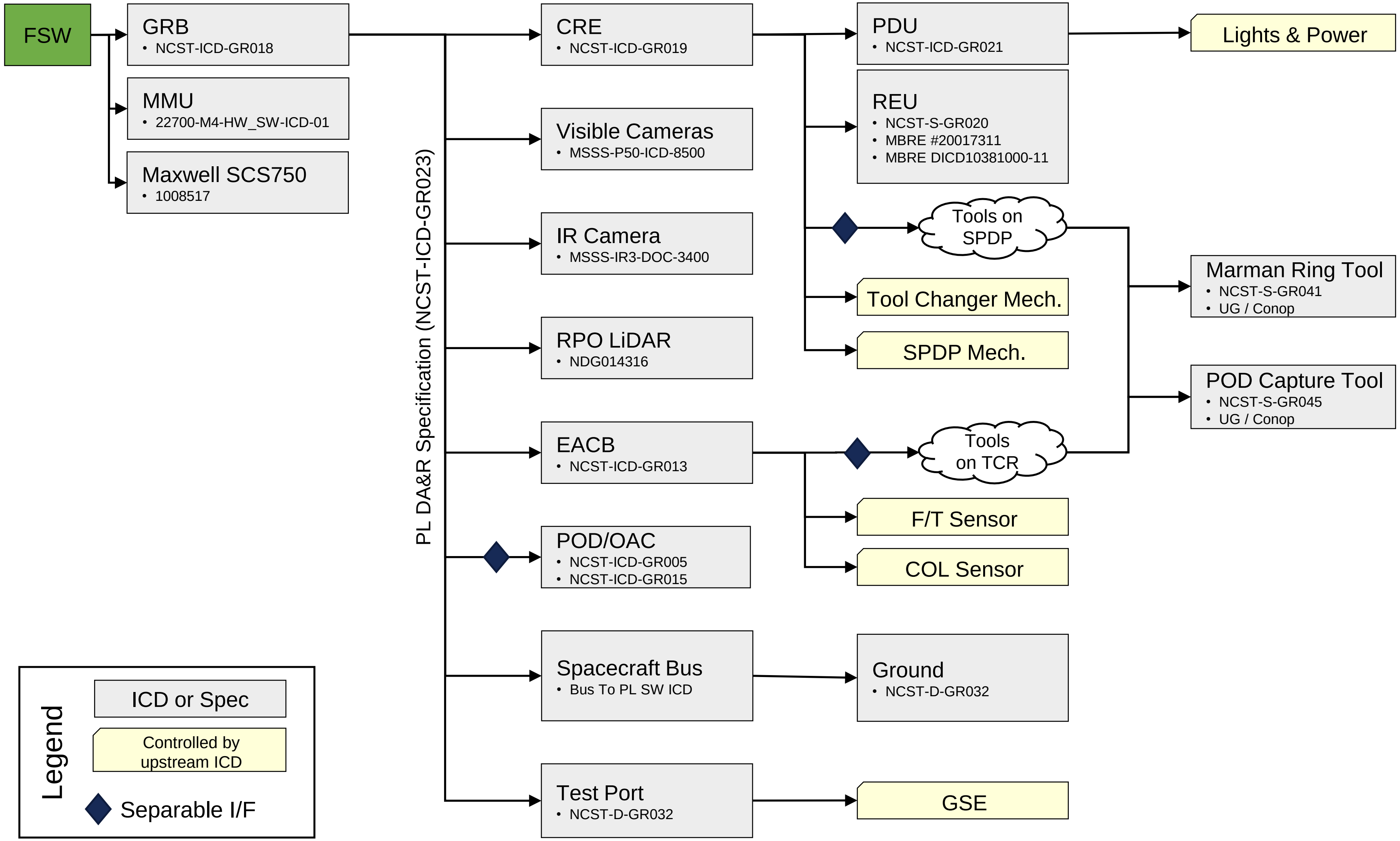
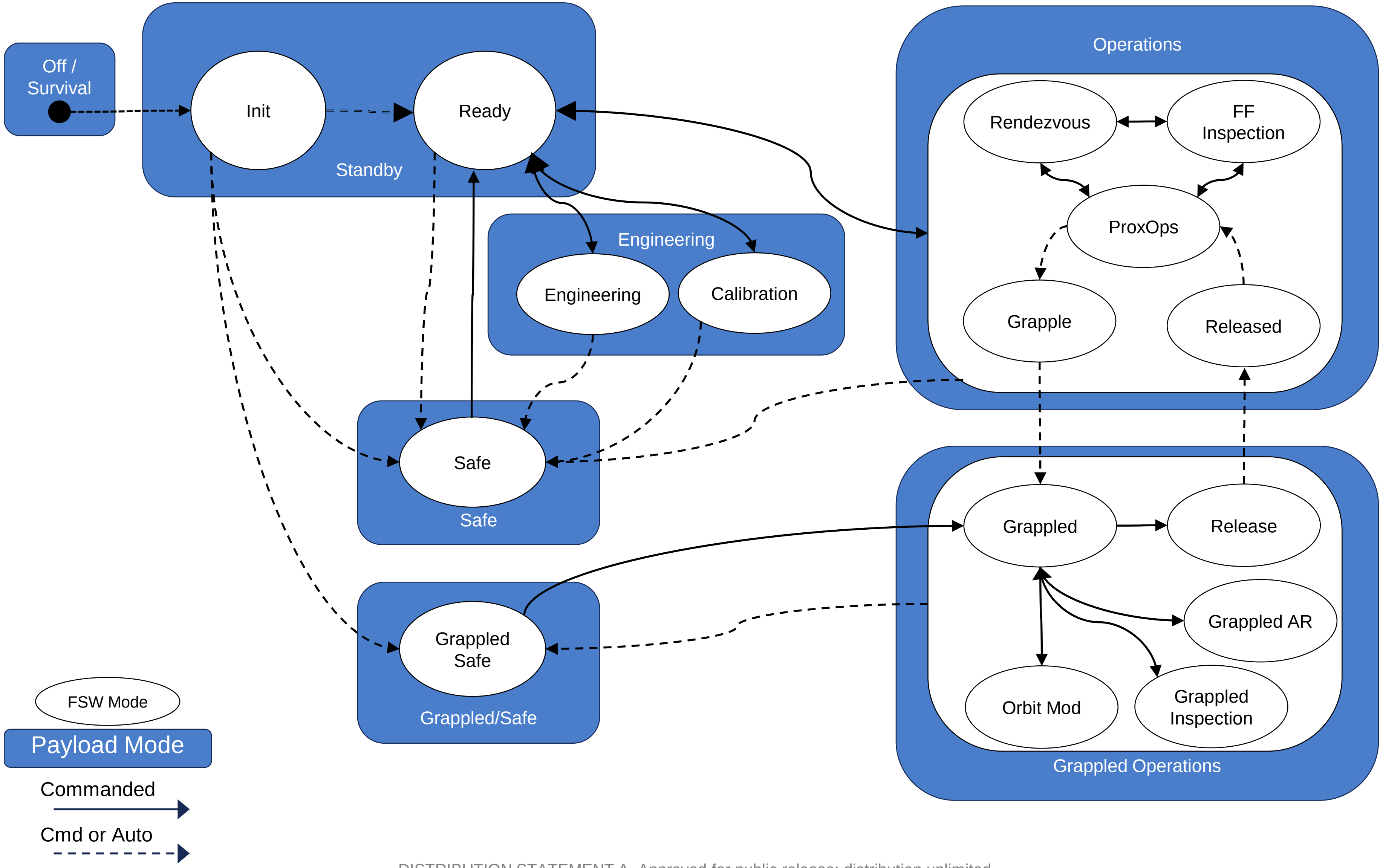
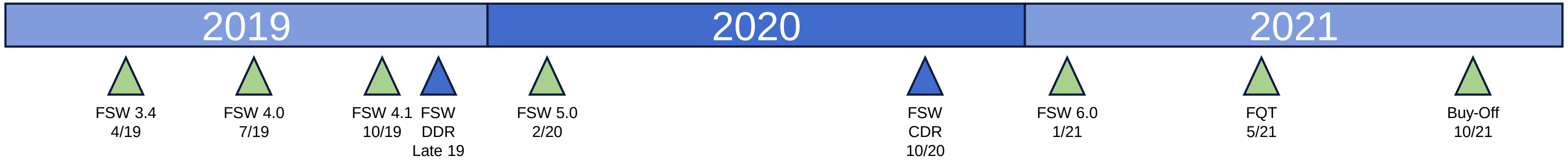
FSW Interfaces



Payload FSW Modes Diagram



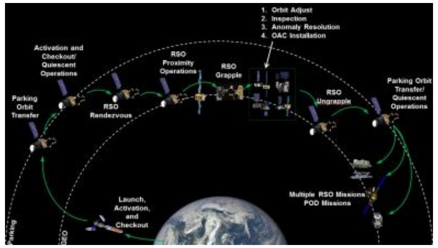
Detailed Software Schedule



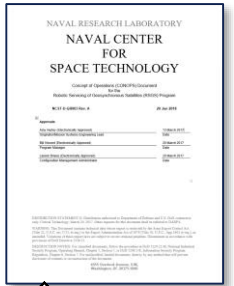
Build	Date	Name	Major Content	Stakeholders
FSW 3.4	4/10/19	MP I	• Initial position control • Joint control • PMM triggers	• Box Test
FSW 4.0	7/10/19	MP II	• Position Control • Machine Vision • Scripting	• ROTB
FSW 4.1	October 2019	VS & FM	• Visual Servoing • Tool Changing • PMM Scripts & Responses • Fault Indicators	• ROTB • RTB • FSW Verification
FSW 5.0	February 2020	Full Robotic Capability	• Tool control	• ROTB • RTB • FSW Verification
FSW 6.0	February 2021	Bus Interfaces Full Mission Capability	• Bus Interfaces • Mission/Bus FM	• ROTB • RTB • FSW Verification

Mission Planning and Integrated Robotics Workstation

Concept of Operations, PSM, Payload Operational Procedures



Concept of Operations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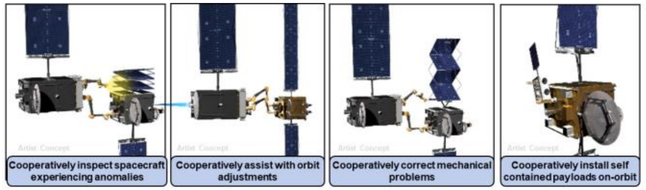
NAVAL CENTER FOR SPACE TECHNOLOGY



Phase/Step	Title
1.0	Phase 1: RMMV Launch, Initial Activation, and Checkout
2.0	Phase 2: RMMV Parking Orbit Transfer
3.0	Phase 3: RMMV Activation and Checkout/Quiescent Operations
4.0	Phase 4: RSO Rendezvous
5.0	Phase 5: RSO Proximity Operations
6.0	Phase 6: Cooperative RSO Grapple
7.0	Phase 7: RSO Orbit Modification
8.0	Phase 8: Cooperative RSO Release
9.0	Phase 9: RSO Inspection (Free Flyer)
10.0	Phase 10: OAC Installation
11.0	Phase 11: RSO Inspection (Grappled)
12.0	Phase 12: RSO Anomaly Resolution (Grappled)
13.0	Phase 13: POD Approach
14.0	Phase 14: POD Capture and Stow
15.0	Phase 15: RMMV Parking Orbit Transfer/Quiescent Operations

- **Phase State Matrix (PSM)**
  - **Captures Mission Phases**
    - **Steps/Sub-Steps**
  - **Captures CONOPS quantitatively**
    - **RMMV Configurations**
    - **States and Modes information**
    - **Operational durations**
  - **Used for:**
    - **Payload Subsystem analysis**
      - **Data budgets**
    - **Requirements development**
    - **Design trades**
  - **Iterates with:**
    - **Operational flows**
    - **FSW use cases**
    - **Design trades**

Mission Phases	Phase 6: Cooperative RSO Grapple
Steps	Step 6.16: Perform Autonomous Grapple
Sub-Steps	Sub-Step 6.16.2: RA enabled for grapple
Operation procedures	Payload Operations Procedures 6.16.2.5

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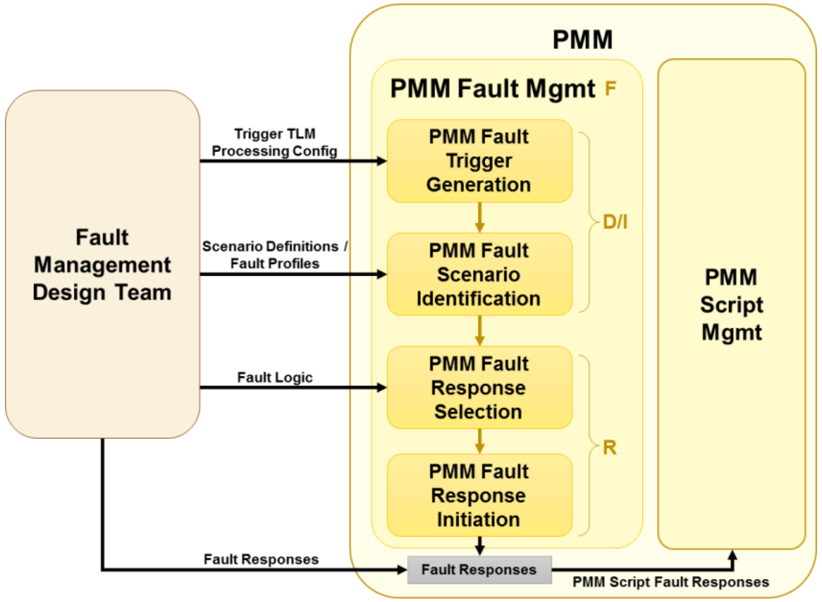
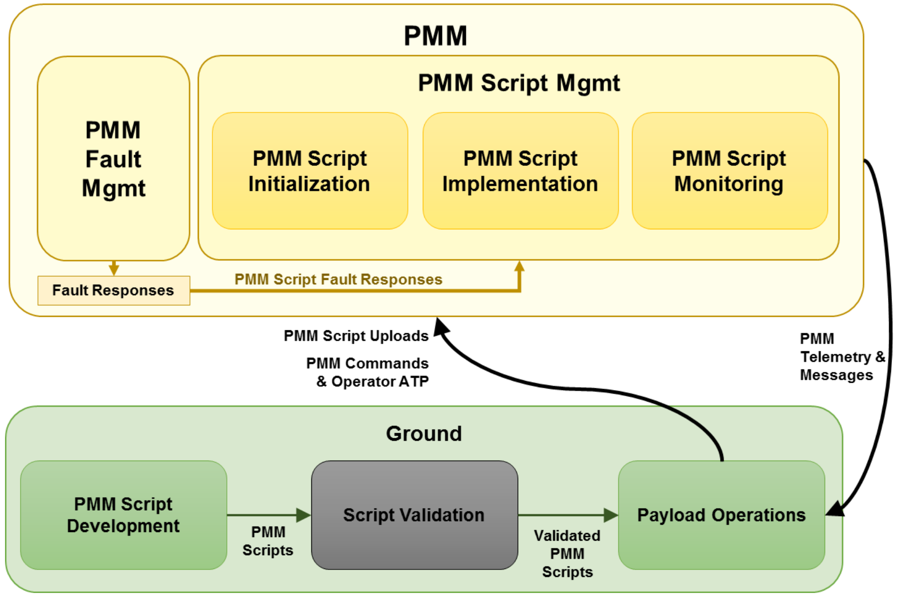
Payload Mission Manager (PMM) and Payload Fault Management (FM) Overview

- The PMM is implemented in FSW and has 2 primary roles:
  - Provide automated, supervisory, and autonomous control of payload to operator (defined in controls section)
  - Provide coherent payload Fault Management capabilities
- PMM scripts are developed by Operators to be executed onboard by the PMM application in FSW
- FM is developed by the Payload Fault Management Team (SE) and implemented via PMM, FSW, and hardware
  - Protects the Payload and the operation (RSO) from a fault when ground is too slow to respond or unable to respond. And protects the health and safety of Payload from some standard operator errors (not malicious).



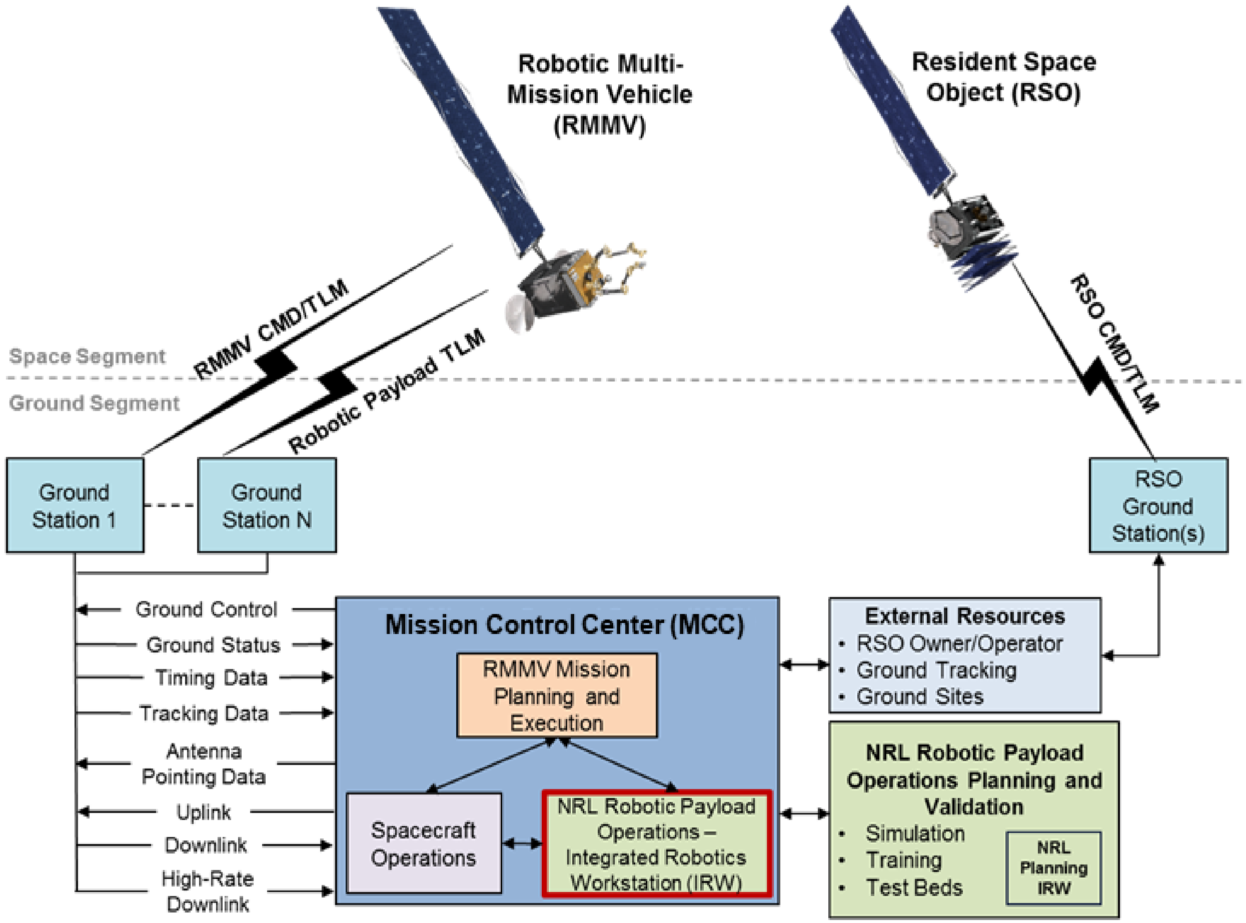
Fault Management interface with PMM



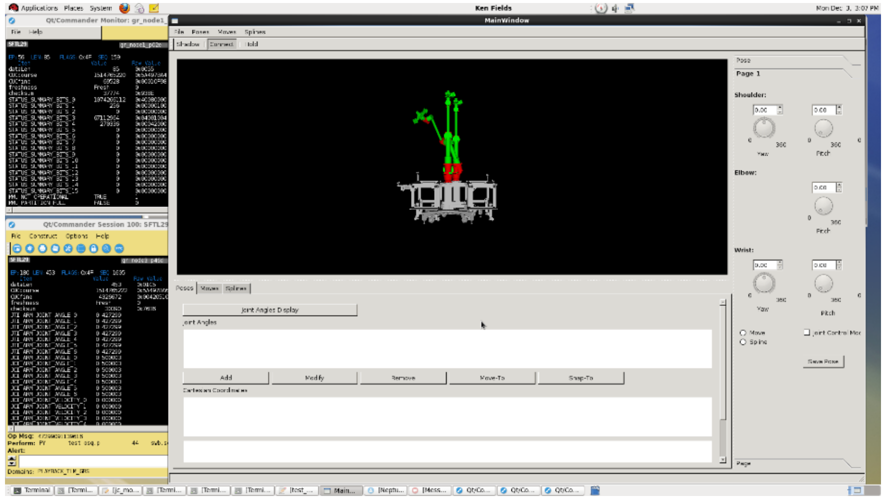
PMM Operations

Integrated Robotics Workstation (IRW) Overview

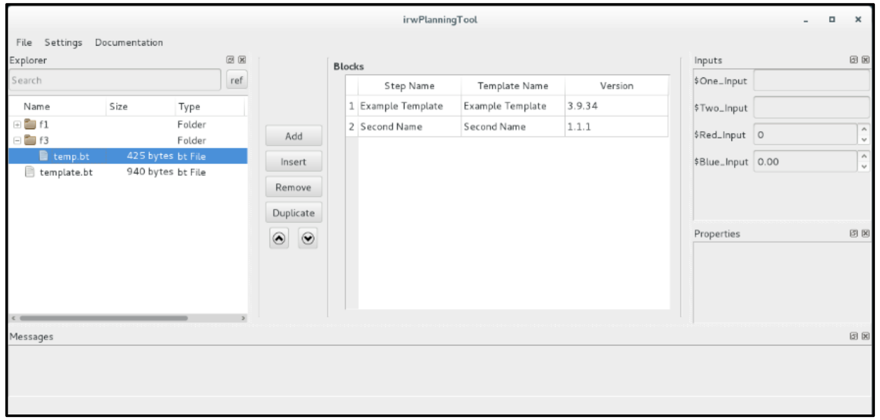
- IRW functions as payload control element in the ground system
  - IRW also provides payload control functions for NRL's test bed assets
- Used for
  - Planning payload operations
  - Verifying payload operations plans
  - Executing payload operations
    - Scripted operations
    - Teleoperations
    - Operator situational awareness
  - Analyzing payload operation results
- Communicates to the Robotics Payload through the Mission Control Center and the RMMV bus



IRW – Notional Desktop



Robot Motion Planner and Visualizer



Operation Planning Tool

Input to tool

Fault Triggers	Scenario	1 Three Faults	2 Just A fault	3 Just B fault	4 Just C fault
1	SensorA_fault	TRUE	TRUE	DC	DC
2	SensorB_fault	TRUE	DC	TRUE	DC
3	SensorC_fault	TRUE	DC	DC	TRUE
4	two_of_A_B_C	DC	DC	DC	DC
	Fault Message	1	2	3	4
	Fault Response	1	2	3	4
	Backstop Timer	0	0	0	0

Tool Output

Fault Triggers	Scenario	1 Three Faults	2 Just A fault	3 Just B fault	4 Just C fault
1	SensorA_fault	TRUE	TRUE	DC	DC
2	SensorB_fault	TRUE	DC	TRUE	DC
3	SensorC_fault	TRUE	DC	DC	TRUE
4	two_of_A_B_C	DC	DC	DC	DC
	Fault Message	1	2	3	4
	Fault Response	1	2	3	4
	Backstop Timer	0	0	0	0
		MULTI	MULTI	MULTI	MULTI
		2	1	1	1
		3	3	2	2
		4	4	4	3

GOOD
ALWAYS Scenario always triggers
UNSAT Scenario never triggers
MULTI Scenario has some overlap with another
MULTI Scenario is a subset of another
DUPL Scenario has an exact duplicate

Key for tool entries:
TRUE for true
F for false
DC for don't care

Operation Verification Tool

Payload & Mission Level Analyses

Verification & Validation Plan

Payload Operational Verification Groupings

Mission	Payload Function
Inspection (Far and Grappled)	RSO Grapple (MRT)
	RSO Release (MRT)
	RPO Support
	Far Inspection
	Grappled Inspection
Orbit Modification	RSO Grapple (MRT)
	RSO Release (MRT)
	RPO Support
	Tool Changing
	Orbit Modification
Anomaly Resolution	RSO Grapple (MRT)
	RSO Release (MRT)
	RPO Support
	Tool Changing
	Force Application
OAC Installation	RSO Grapple (MRT)
	RSO Release (MRT)
	RPO Support
	POD Grapple
	POD Stow
	OAC Placement & Detach

11 Unique Payload Functions	Verification Grouping
• RPO Support • Far Inspection • Grappled Inspection	**Inspection & RPO Support**
• RSO Grapple (MRT) • RSO Release (MRT) • POD Grapple	**Grapple and Release**
• Tool Changing • OAC Placement & Detach • POD Stow	**Pick and Place**
• Orbit Modification	**Orbit Modification**
• Force Application	**Force Application**

Grapple & Release V&V Plan (Example from Payload PDR)

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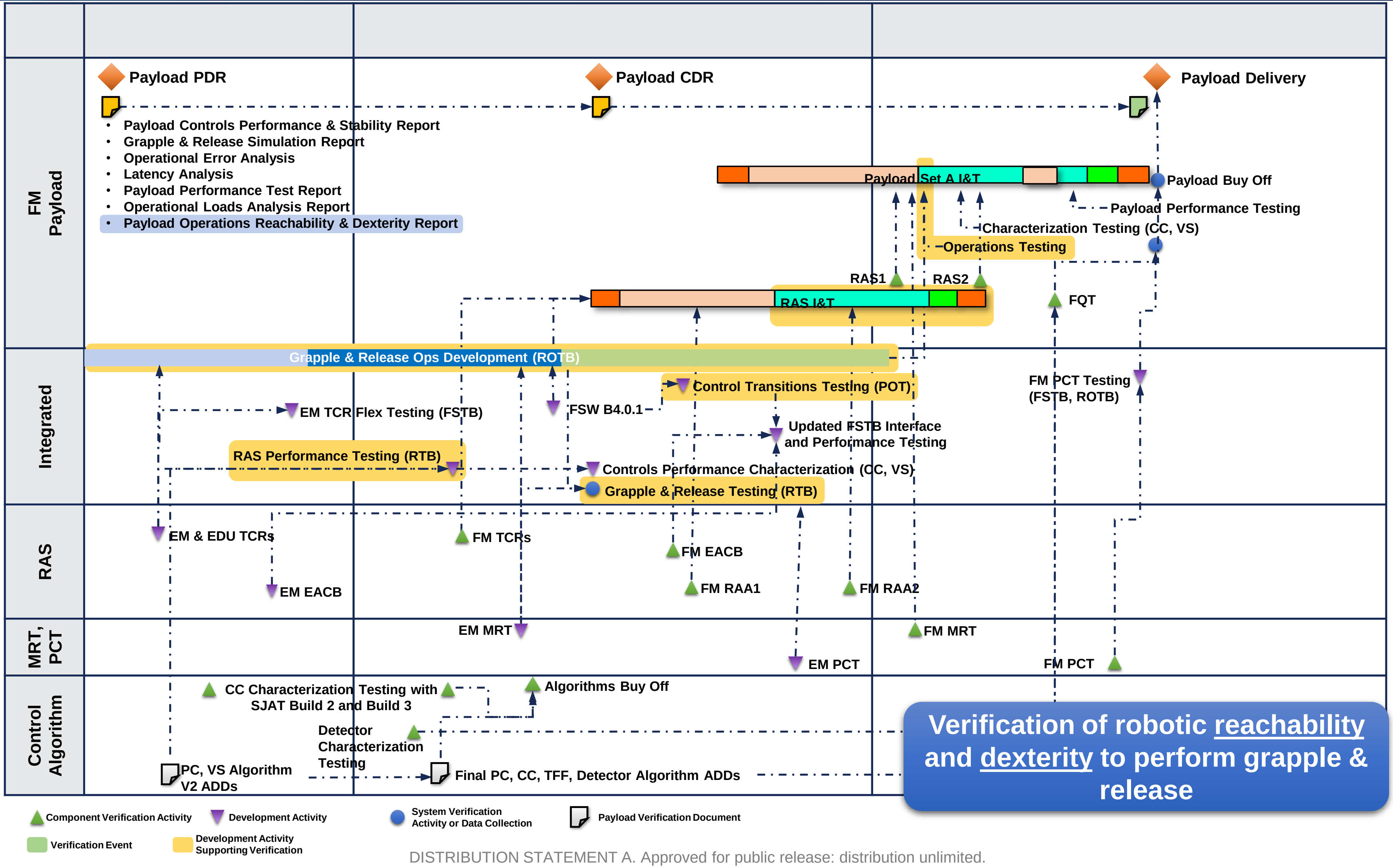

Verification of robotic reachability and dexterity to perform grapple & release

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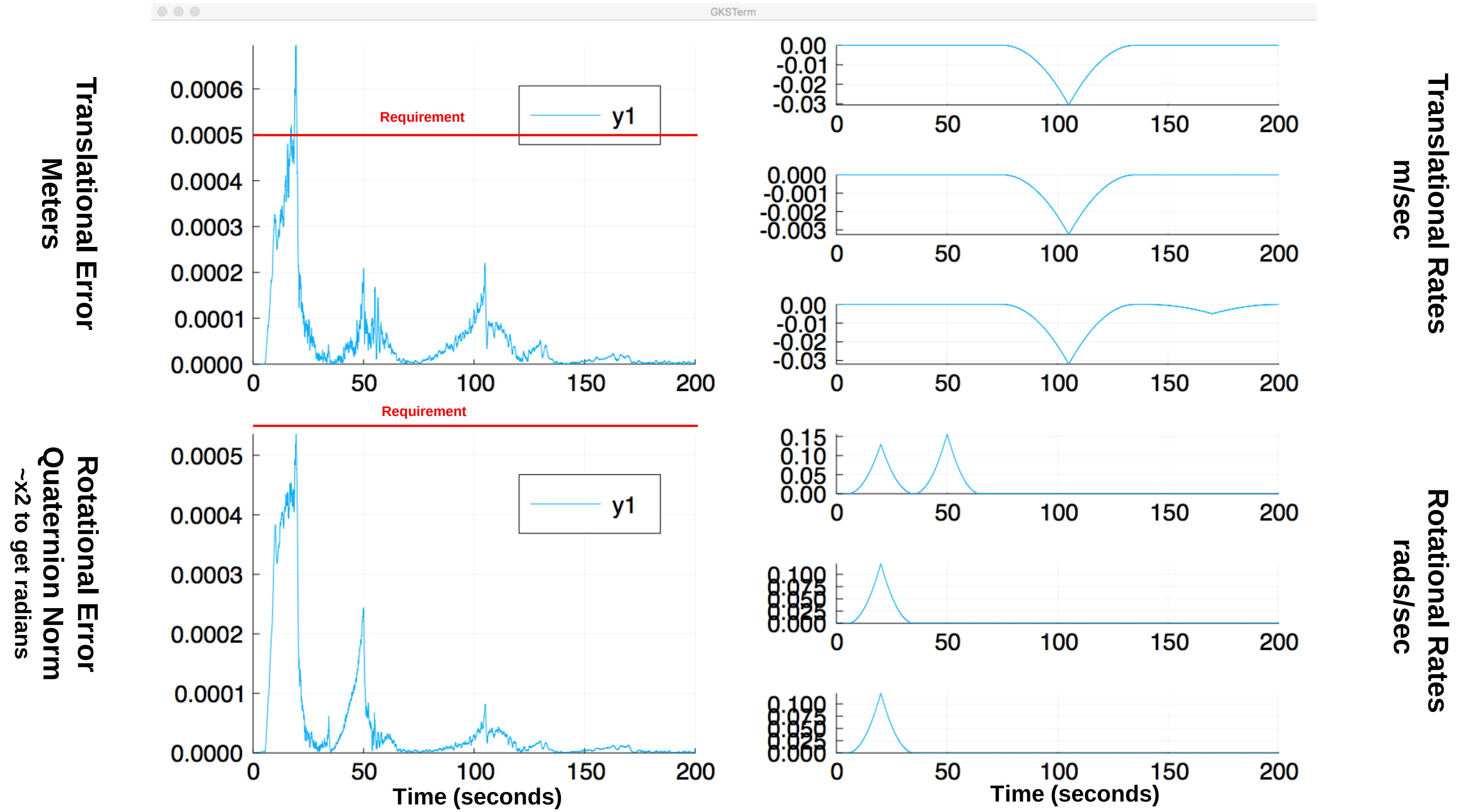
Payload Controls Analyses

Free-Space Motion: Position Control Preliminary Results

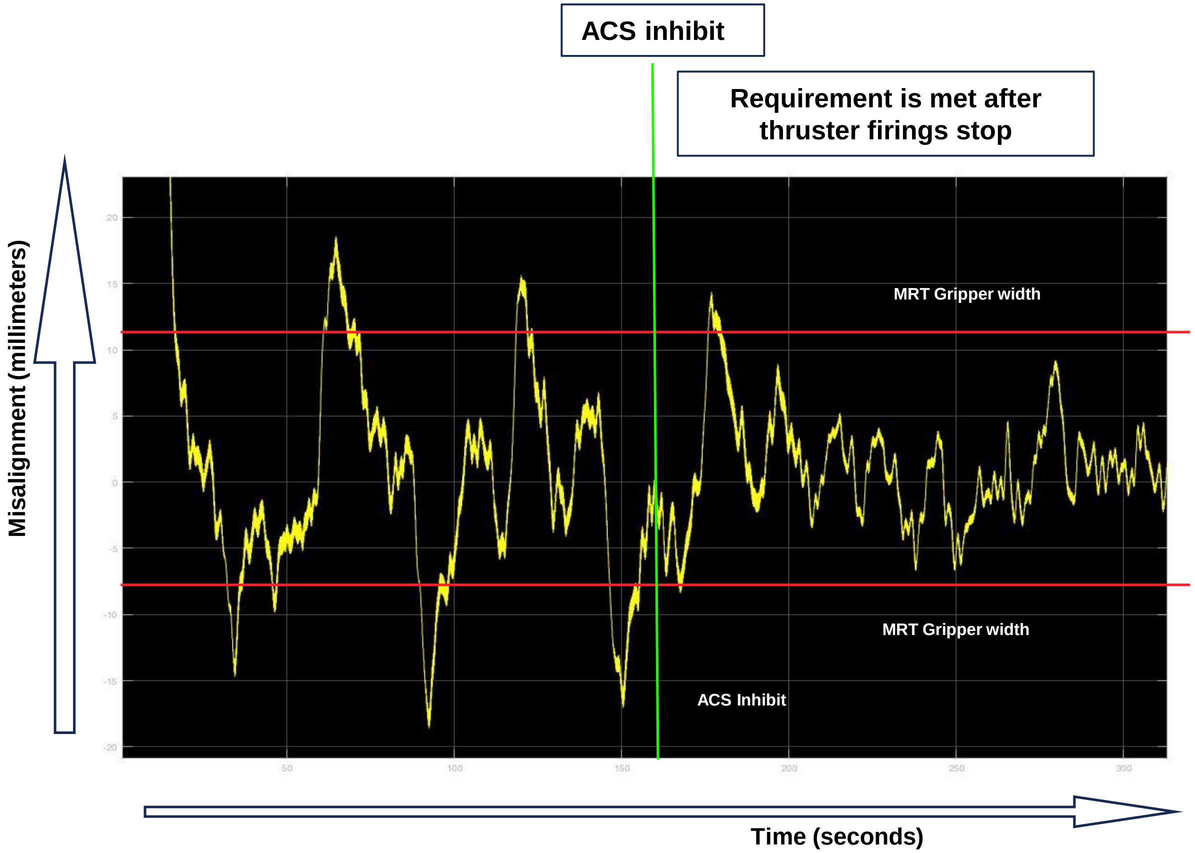


- Note that:
  - IK is running in real time with 20% margin (albeit on a non–flight processor)
  - IK is using non–gradient–based optimizer; gradient–based optimizer should improve running speed ~5x, and error ~2–3x

Position Control meets tracking performance requirements

Visual Servo System Performance

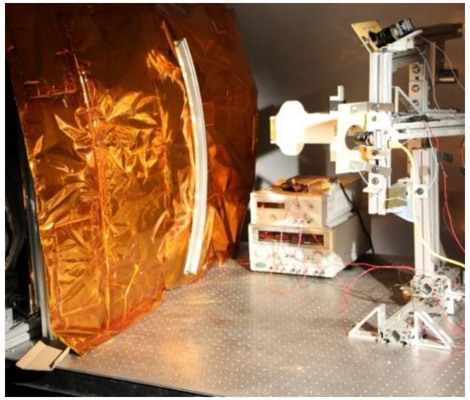
- Visual Servo simulation performed to assess tracking performance
  - Marman detector noise model was used
  - Assumed worst case servicer to RSO relative rate of 7 mm/sec
  - Assumed worst case instantaneous direction change at edge of capture box
  - Assumed worst case camera-to-ring distance of 0.7 m (noise improves with decreased range)
    - Performance spec must be met at <0.5 m)



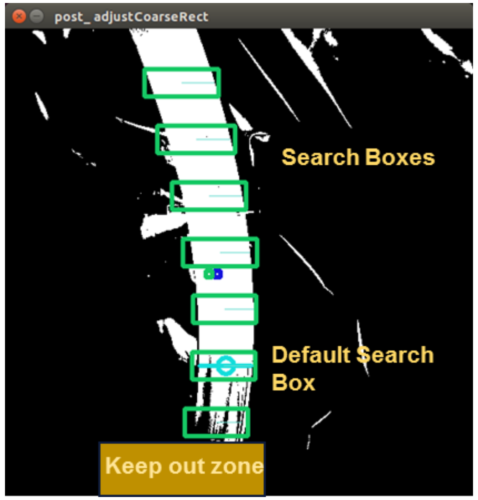
Visual Servo System meets tracking requirements

Machine Vision Subsystem Testing

- Performance Requirement:
  - Bias < 3 mm
  - Noise < 5 mm (2σ)
- Test configuration:
  - Variable lighting, blanketing, ring types, and alignment geometries per the RSO IDD
- Preliminary Results:
  - Bias < 2.5 mm (range dependent)
  - Noise < 2.3 mm (1σ) (range dependent)
- Image sequences have been analyzed with the MRD and results have been used to generate a mathematical noise model that represents MRD performance
  - Noise model is used in Visual Servo analysis and the MissionSim



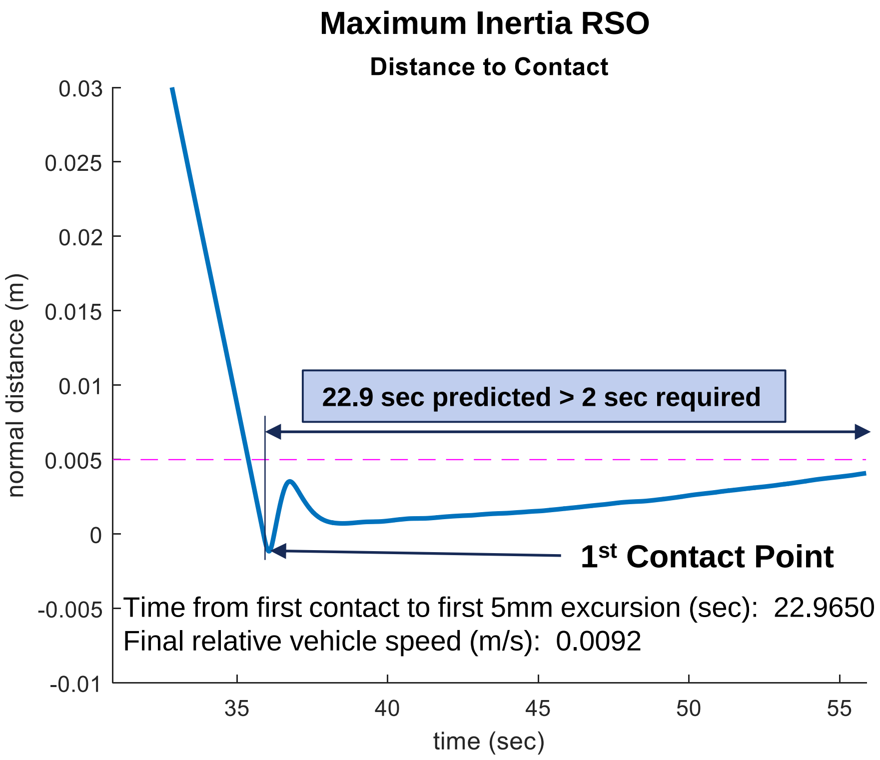
Machine Vision Lab Set Up For Marman Ring Testing

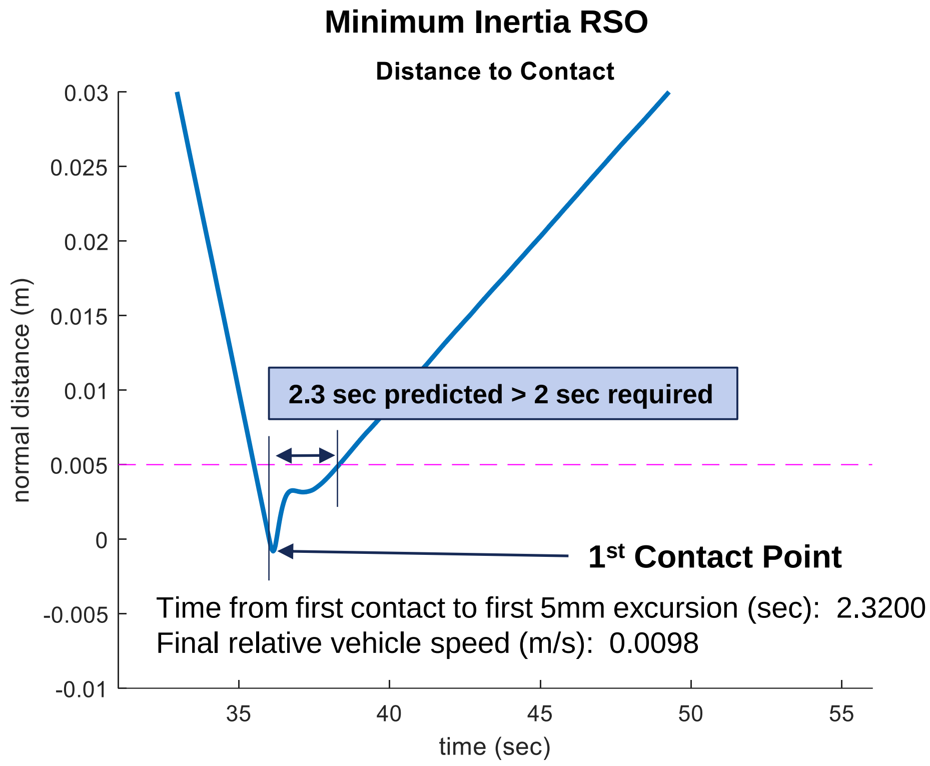


Machine Vision meets requirements over a range of blanketing, lighting, and ring configurations

Marman Ring Grapple: Preliminary Simulation Results

Simplified rigid-body planar 3-joint simulation of Marman Ring grapple predicts that a 10 mm/s approach rate will yield adequate time (> 2 seconds) to close the gripper before excessive separation develops between the tool and Marman Ring.

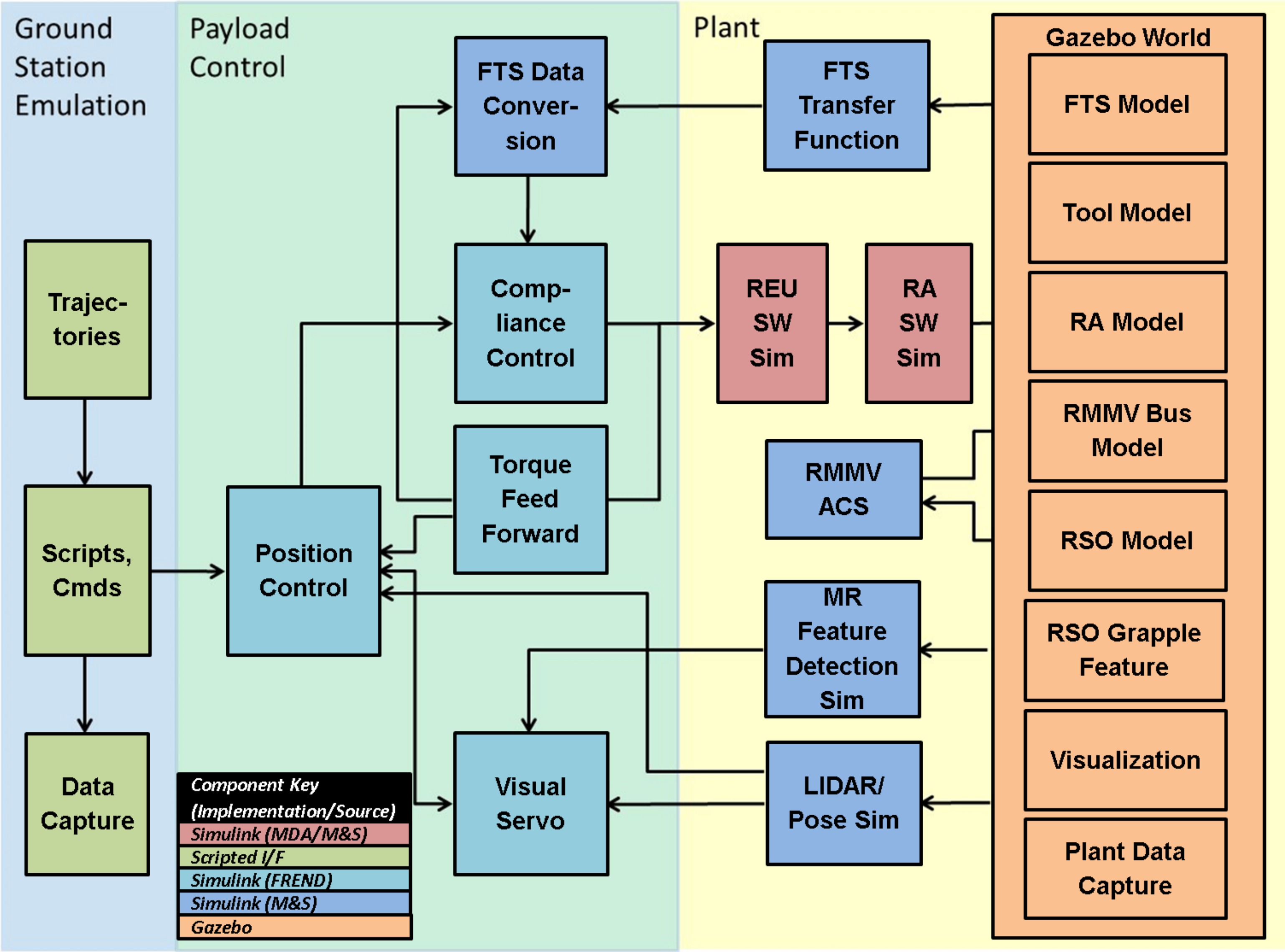




Note - Compliance Control is operating continuously (not triggered upon contact). Trigger will be simulated for CDR level analysis.

Compliance control meets requirements across RSO IDD cases

MsnSim Simplified Block Diagram (Build 2)



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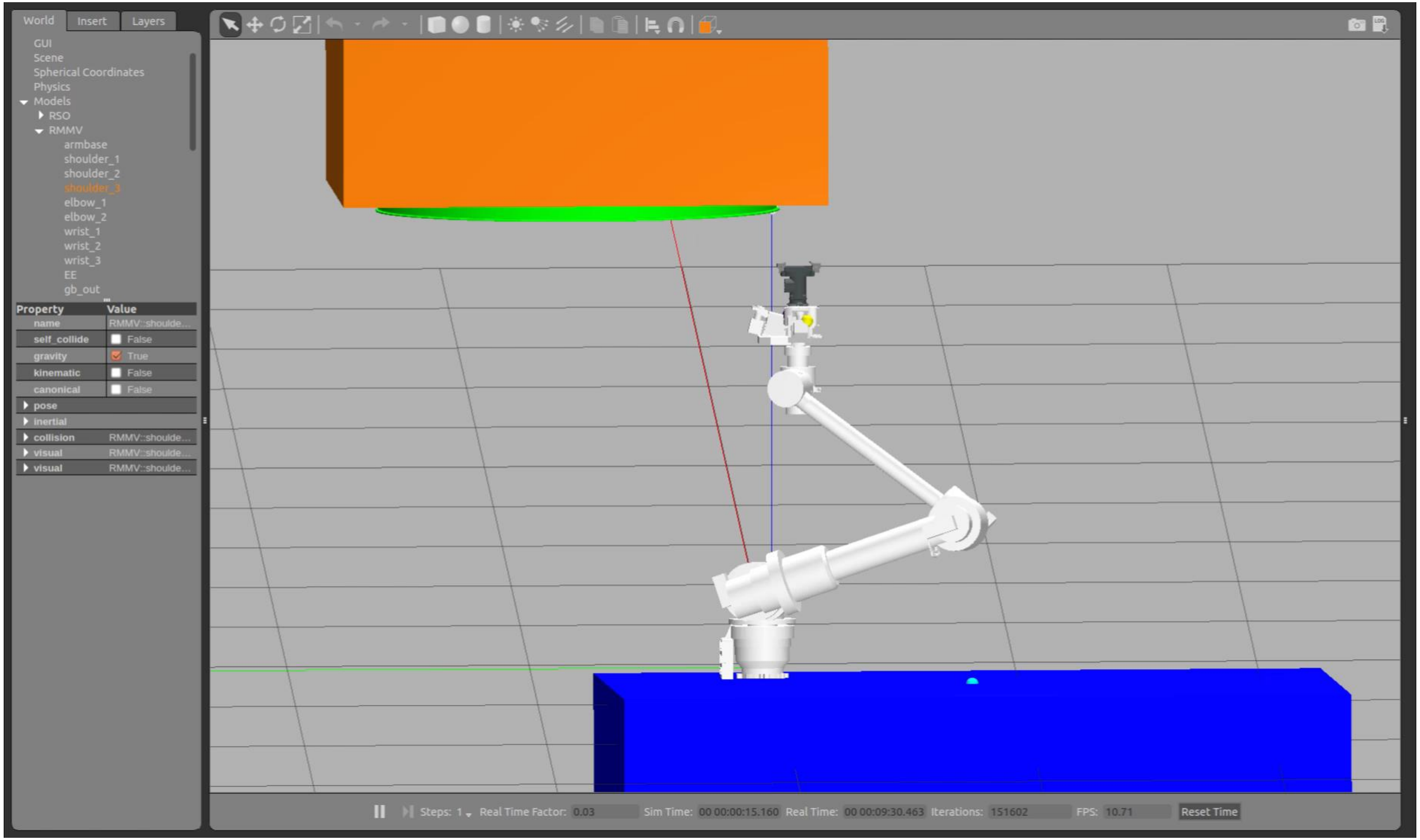
MR Grapple Animations



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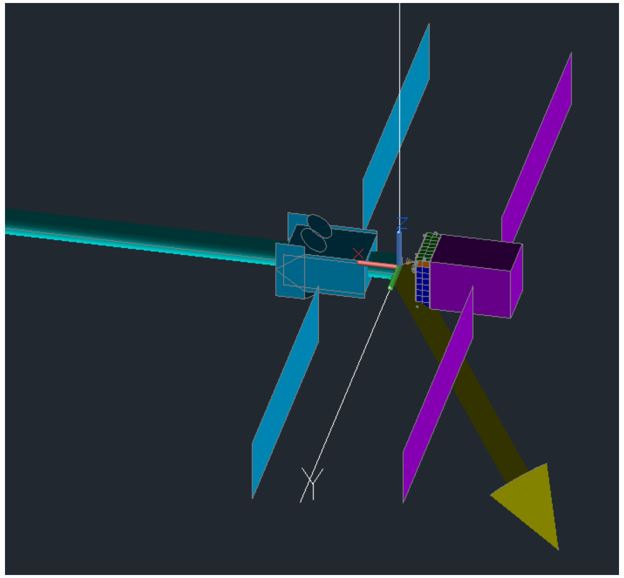
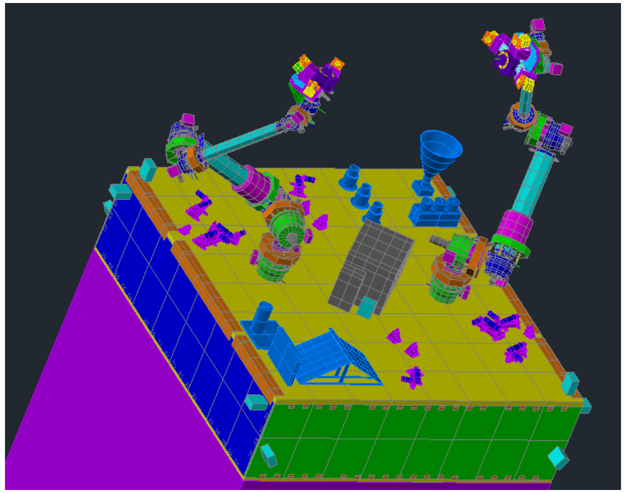
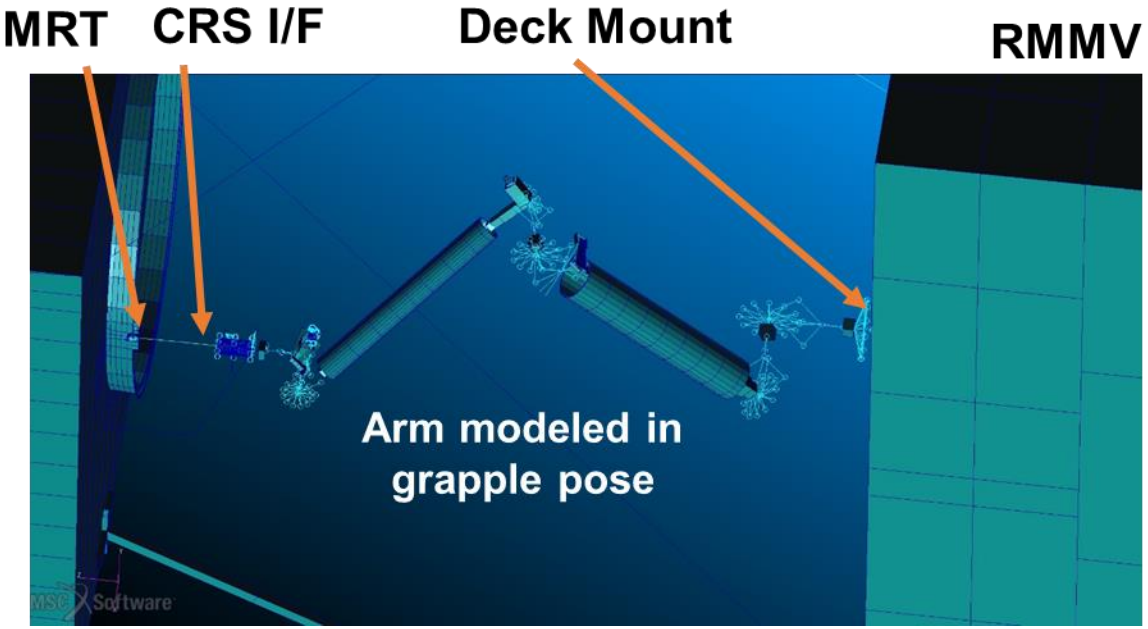
Payload Structural and Thermal Analyses

Structures and Thermal Design and Analysis

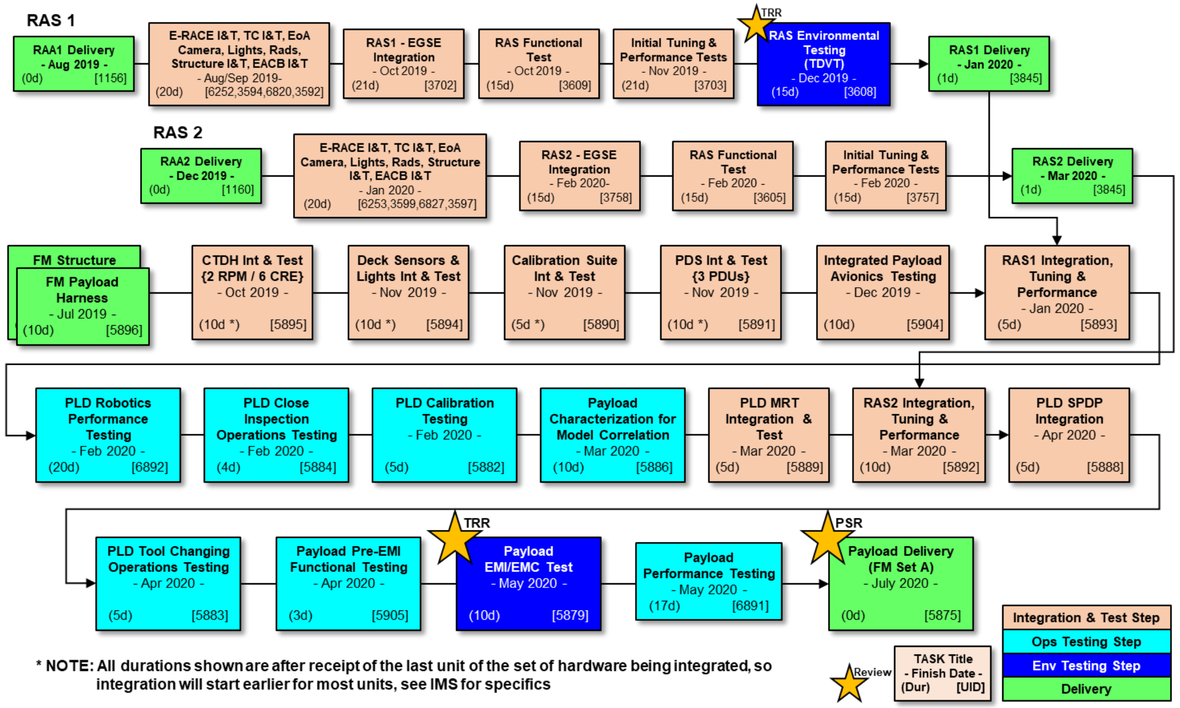






- Structural and thermal models and analysis processes have been built
- Initial results show a wide range of payload operability
- Partner bus performance characteristics and operations details will be used to update analysis results
- Customer specific analyses are also expected

I&T and Mission Operation Plans

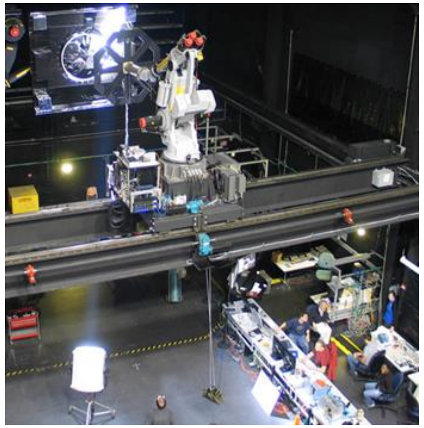


* NOTE: All durations shown are after receipt of the last unit of the set of hardware being integrated, so integration will start earlier for most units, see IMS for specifics

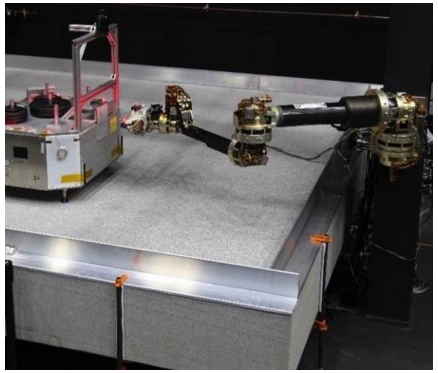
Purpose	**Development** Operational Flow Development and Validation Procedure Development and Validation Process Development and Verification HW and SW Requirements Validation Personnel Skill Development		**Verification** Operational Requirements Verification Final Operational Flow Verification Final Procedure Verification High Level HW and SW Verification		**Flight** Demo RSO Ops Procedures Rehearsals Training
Phase	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**
Schedule (end date)	Payload PDR+60 10 / 2018	Payload CDR 6 / 2019	RAS #1 I&T 2 / 2020	Payload PSR 6 / 2020	Launch 3/2021
Description	- **Personnel skill development** - Develop Operational Flows - Develop Procedures - Validate key requirements - Inform PMM development - Inform FDIR development - Support subsystem development	- **Move to early FSW** - **Mix of BB and EDU HW** - Validate FSW - Verify Operational Flows - Verify Procedures - Mature PMM - Mature FDIR - ***Support Subsystem I&T***	- **FSW** - **EDU and EM HW** - **Verify Flight Operational Flows** - **Verify Flight Procedures** - Validate FSW - Verify Flight PMM - Verify Flight FDIR - ***Support Subsystem I&T***	- Verify FSW - **Verify Flight HW** - Verify Flight Operational Flows - Verify Flight Procedures - Verify Flight PMM - Verify Flight FDIR	- Develop Demo RSO Ops - Generate Procedures - Ground Tests and Rehearsals - Operator Training
Test Bed	**ROTB:** HW: COTS arm, BB support HW EGSE: ROTB Rack SW: Legacy RTB SW PMM: N/A - Director / Procedure FDIR: N/A - Director / Procedure IRW: Prototype	**ROTB** and **RTB:** HW: **COTS arm** and: **EDU arm** with EDU/EM support HW EGSE: RTB **SW: FSW Build 3&4** PMM: Early scripts FDIR: Early logic IRW: Build 0/1 GOT/POT as needed	**RTB:** HW: **EDU arm**, EDU/EM support HW EGSE: STB **SW:** FSW 4 **PMM:** core scripts (unverified) **FDIR:** core logic (unverified) **IRW:** Build 2 GOT as needed	**FTB:** **Flight Arms**, flight P/L HW **SW:** FSW 4+ **PMM:** core scripts **FDIR:** core logic **IRW:** Build 2	**Ground Test Beds:** **HW:** Updated ROTB **SW:** FSW 4+ **PMM:** verified scripts **FDIR:** verified logic **IRW:** Build 2+

Facilities

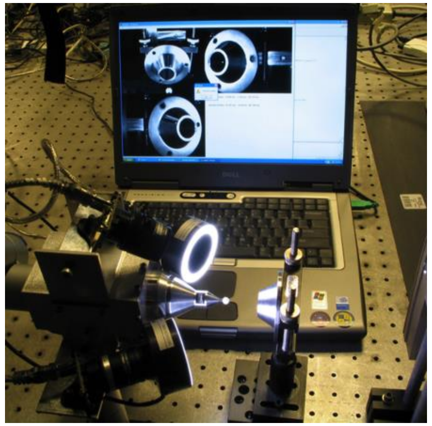
NRL Major Facilities for Satellite Servicing and In-Space Assembly



Proximity Operations Testbed
Facilitates full scale hardware-in-the-loop rendezvous docking and servicing rehearsals

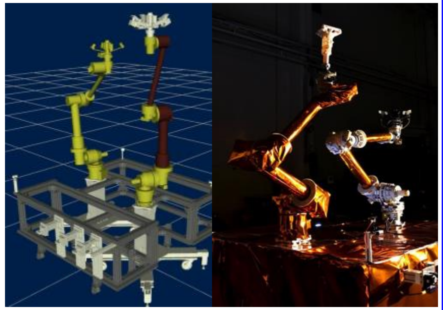


Gravity Offset Testbed
Large air-bearing table facilitates high precision contact dynamics rehearsal and validation



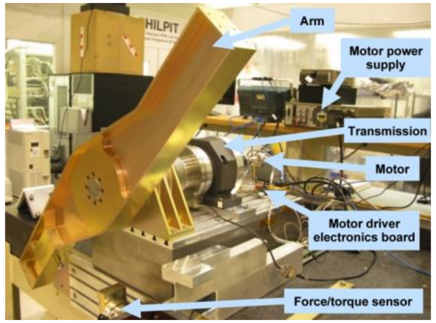
Machine Vision Lab
Optical testbed for development and characterization for flight machine vision sensors, illuminators, and algorithms

Robotic Operations Testbed
Enables integrated procedure development, testing, and training of RSGS end-to-end operations on non-flight system

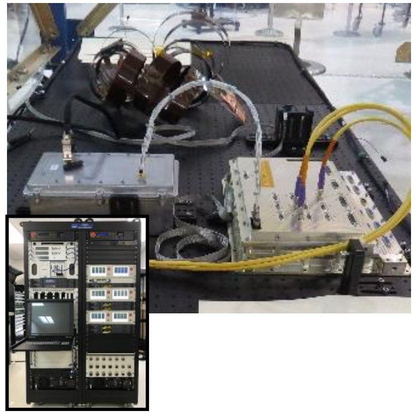


Modeling and Simulation
Robust Monte-Carlo simulation capability validates performance of robotic operations

Integrated Robotics Workstation
Robotic operations control station, supports high fidelity rehearsals and training



Single Joint Actuator
Provides extremely detailed correlation between predicted robotic hardware behavior and controls simulations

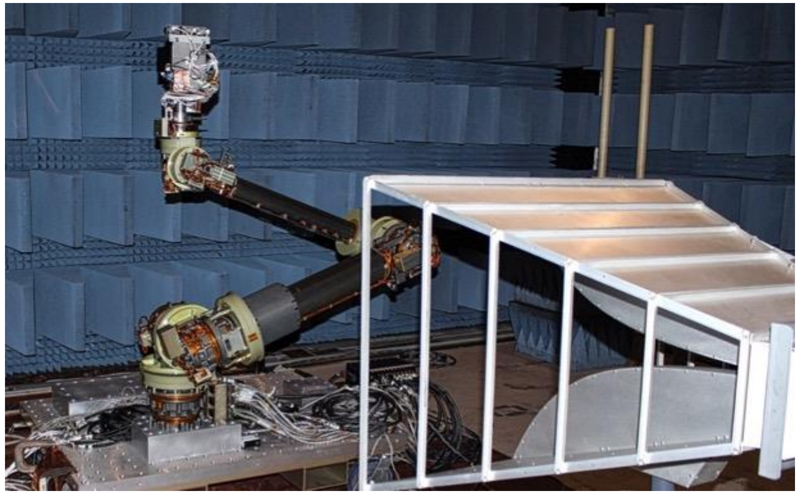


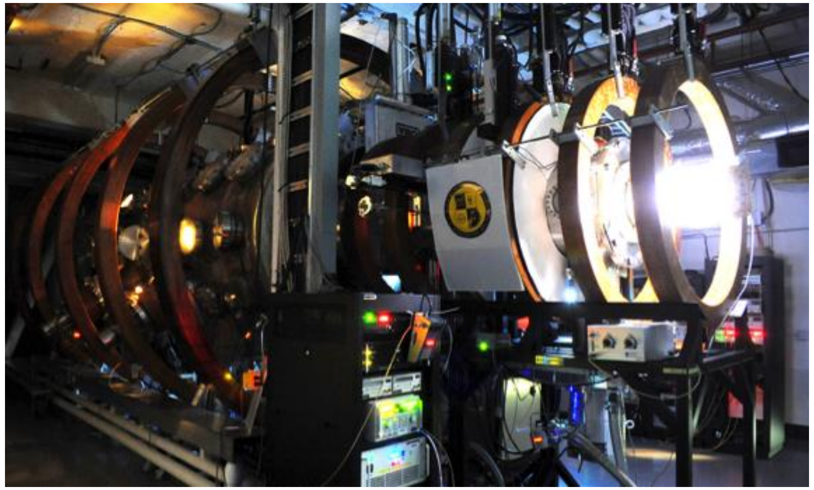
Flatsat Testbed
Integrated avionics testbed facilitating end-to-end test of payload electronics

NRL Environmental Test Facilities


Thermal Vacuum Chamber


Vibration and Shock Lab


EMI Chamber


Space Charge/Plasma Chamber

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